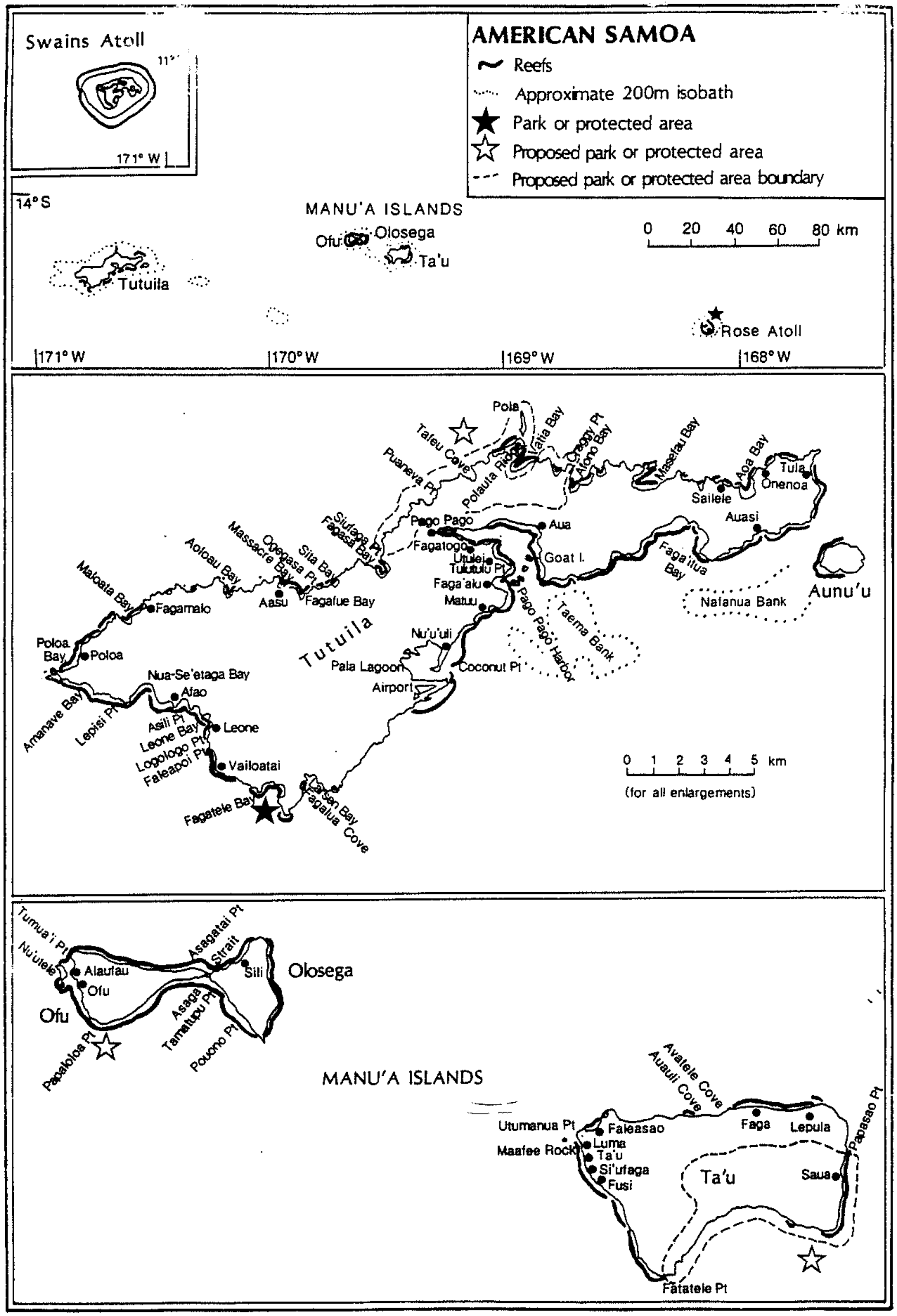
CORAL REEF
REFERENCE PAPERS


AMERICAN SAMOA
Reefs
Approximate 200m isobath
Park or protected area
Proposed park or protected area
Proposed park or protected area boundary
Swains Atoll
171° W
14° S
MANU'A ISLANDS
Ofu
Olosega
Ta'u
Tutuila
Rose Atoll
0 20 40 60 80 km
171° W
170° W
169° W
168° W
Pola
Tafeu Cove
Vatia Bay
Craggy Pt
Afono Bay
Masefau Bay
Aoa Bay
Tula
Onenoa
Sailele
Auasi
Puaneva Pt
Polauta Ridge
Pago Pago
Aua
Fagatogo
Utulei
Tutuila Pt
Goat I.
Faga'itua Bay
Faga'alu
Matuu
Pago Pago Harbor
Taema Bank
Nafanua Bank
Aunu'u
Siufaga Pt
Fagasa Bay
Sita Bay
Oneqasa Pt
Massacre Bay
Aoloau Bay
Maloata Bay
Fagamalo
Aasu
Fagafue Bay
Tutuila
Nu'u'uli
Pala Lagoon
Coconut Pt
Airport
Poloa Bay
Poloa
Nua-Se'etaga Bay
Afao
Amanave Bay
Lepisi Pt
Asili Pt
Leone Bay
Leone
Logologo Pt
Faleapoi Pt
Vailoatai
Fagatele Bay
Larsen Bay
Fagalua Cove
0 1 2 3 4 5 km
(for all enlargements)
Tumua'i Pt
Nu'utele
Alaufau
Ofu
Asagatai Pt
Strait
Sili
Olosega
Asaga
Tamatupu Pt
Pouono Pt
Papaloloa Pt
MANU'A ISLANDS
Avalele Cove
Auauli Cove
Papasao Pt
Utumanua Pt
Faleasao
Faga
Lepula
Maafee Rock
Luma
Ta'u
Si'ufaga
Fusi
Ta'u
Saua
Fatatele Pt

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION IX
75 Hawthorne Street
San Francisco, Ca. 94105-3901

W-7-1

08 DEC 1992

In Reply
Refer To W-5-1

Mr. Donald B. Cataluna
Hilo Coast Processing Company
P.O. Box 18
Pepeekeo, Hawaii 96783-0018

Dear Mr. Cataluna:

This is in response to your letter of September 17, 1992, requesting deletion or reduction of a number of the receiving water monitoring requirements contained in your NPDES permit No. HI 0000191. We acknowledge that the closure of your sugar mill operations in two years will significantly reduce and change the nature of the impacts of your discharge on the receiving waters. We therefore tentatively support some of the reductions in the monitoring requirements of permit Part D that you propose, as discussed below.

First, we would like to emphasize that the lead NPDES agency in Hawaii, with the delegated authority to issue and modify permits, is the Hawaii Department of Health. In order to effectuate changes in the current monitoring requirements of the permit, a formal permit modification request must be sent to DOH and the applicable modifications must be carried out by the State. We have discussed the guidance that follows with DOH and are in agreement with the State on the appropriate ambient monitoring requirements for the remainder of your permit period, as well as on the process for converting the existing permit to one that authorizes the discharge of only storm and cooling waters.

Because of the greatly reduced volume of sediment discharges that should accompany cessation of sugar cane processing at the Pepeekeo Mill, EPA tentatively supports deletion of the sediment monitoring program required by permit Part D.4, as you request. In addition, we consider that the benthic monitoring program required by Part D.5 may be pared back somewhat as a result of the future change in your operations. Our comments below on the nature of the reductions we would accept are based on the benthic monitoring program proposed in your letter to Hawaii DOH of April 29, 1992, including the changes requested by us in our letter to you of August 3, 1992.

It is imperative that some benthic monitoring be conducted during the next two years in order to assess the current condition of the coral communities and other benthic organisms prior to closure of the sugar mill and commencement of cooling water-only discharges. Information obtained from this program will be of great value in assessing baseline conditions at the start of your cooling and storm water discharges in 1994 and in designing an appropriate receiving water monitoring program for inclusion in a subsequent permit authorizing those discharges.

EPA would thus appreciate re-submission of a Benthic Community Structure monitoring program, incorporating our prior suggestions and perhaps reduced in scope somewhat as described below, but as expeditiously as possible in order to obtain at least three samples or observations within the next two years. The survey stations described on page 3 of "A Proposal to Conduct a Marine Monitoring Program in the Vicinity of the Hilo Coast Processing Company, Pepeekeo, Hawaii" may be narrowed from a total of eight stations to six by deleting monitoring at the 1.5-mile locations in both the north and south direction. EPA's 1989 study showed relatively little change in coral cover beyond a 1 mile range of the discharge point. We also suggest that water quality sampling at the coral survey locations, as described on page 7 of your proposal and including the additions suggested by us in the first paragraph of comment 2 of the "Sedimentation" discussion in our August 3, 1992 letter, be retained as part of the bottom biological monitoring program.

On the other hand, the sediment sampling and analysis program suggested by us in the second paragraph of comment 2 need not be conducted. That is, we continue to consider that water quality monitoring--including analysis for specific toxicants that may be present--is an important component of the assessment of baseline benthic conditions in the vicinity of your discharge. However, with the cessation of the sugar cane processing components of your discharge in two years, the sediment component of the previously-proposed monitoring program is no longer necessary.

The preferred method of implementing the requested changes to your permit is through a formal permit modification, which must be conducted by the State of Hawaii. Given the change in production processes and in the nature of the discharge, it seems appropriate that the modified permit would expire with the cessation of the current, combined sugar mill and thermal discharge. HCPC would then be required to apply for a new permit to authorize the power plant and stormwater discharges. Information obtained from the benthic monitoring program required by the current permit will be useful in completing the permit application for, and evaluating impacts of, the new discharge(s). We suggest that HCPC and Hawaii DOH discuss and decide upon the optimal means of carrying out the conversion from the existing permit to one covering the new discharge after cessation of sugar processing at the Pepeekeo mill.

Finally, EPA considers that the semi-annual receiving water quality monitoring requirements contained in permit Part D.7 should be retained, as a minimum measure of compliance by the current HCPC discharge with receiving water quality standards and as a continuing record of ambient water quality conditions in the vicinity of the discharge. Again, this ambient data could be useful in determining conditions prior to commencement of the new discharge of noncontact cooling and storm waters in two years.

I hope that this guidance is useful to you in revising your proposed marine monitoring program for re-submittal to Hawaii DOH and to us for final approval and go-ahead, as well as in conducting the permit modification to revise the monitoring requirements and possibly the expiration date of your current permit. Please contact me at (415) 744-1877, or Jacques Landy at (415) 744-1920, if you have any questions or concerns.

Sincerely,

Will H. Pierce

William H. Pierce, Chief
Permits and Compliance Branch

cc: Denis Lau
Hawaii Department of Health

Proceedings of the Fifth International Coral Reef Congress, Tahiti, 1985, Vol. 4

REEF CORALS IN KANEOHE BAY SIX YEARS BEFORE AND AFTER TERMINATION OF SEWAGE DISCHARGES (Oahu, Hawaiian Archipelago)

LES CORAUX DE LA BAIE DE KANEOHE : SIX ANS AVANT ET APRES LA FIN DES REJETS D'EGOUTS (Oahu, Archipel des Hawaii)

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ABSTRACT

Watersheds surrounding Kaneohe Bay were dominated by rural and agricultural use before 1939. Reef coral communities flourished on lagoon reef slopes and were protected from the open ocean by a large barrier reef. After 1939, military dredging and filling, residential development, and population growth occurred, especially in and around the confined southeast bay. As population grew, sewage discharges into the lagoon increased, culminating in the construction of large sewage outfalls in the southeast bay by 1963. After 1965, the scientific community, including Maragos (1972), began to study changes in the lagoon. It was speculated that eutrophication and sedimentation, as a result of urbanization and construction, were the cause of an observed decline in lagoon coral communities in the south lagoon and explosive growth of the green algae Dictyosphaeria cavernosa, which was smothering coral, in the middle lagoon. Reef corals in the bay's northwest lagoon remained abundant and appeared unaffected. Pressure from the public and scientific community compelled the local government and military to terminate large sewage discharges in the southeast lagoon by 1978. Now only a minor amount of sewage is discharged in the northwest lagoon. In 1983 we re-surveyed the lagoon and coral transect sites of Maragos (1972) using the same methods. These surveys revealed a remarkable recovery of corals, especially, Porites compessa and Montipora verrucosa, in the southern and middle lagoon and continued high coral abundance in the northern lagoon. Minor coral species, Pocillopora damicornis and Cyphastrea ocellina, also were more abundant in the lagoon. In contrast, Dictyosphaeria declined greatly except for a minor increase in the northern lagoon. This study and other recent investigations corroborate that sewage was a major stress to lagoon corals and a stimulant to Dictyosphaeria growth. In addition, these studies indicate that the detrimental effects of sewage on corals are generally magnified in confined embayments with restricted circulation.

RESUME

Avant 1939, les rivages entourant Kaneohe Bay étaient essentiellement ruraux et utilisés pour l'agriculture. Les communautés coralliennes des pentes lagonaires étaient florissantes, et protégées de l'océan par une large barrière récifale. Après 1939, se sont produit des dragages et remblais pour l'armée, le développement de résidences, et un accroissement de population, particulièrement aux alentours de la partie sud-est de la Baie qui est confinée. Parallèlement à l'accroissement de population, les rejets d'égouts se sont multipliés, avec en particulier la construction d'un grand émissaire dans le sud-est de la baie en 1963. Après 1965, la communauté scientifique, en particulier Maragos (1972) a commençé à étudier les changements dans le lagon. On pensait que l'eutrophisation et la sédimentation, résultant de l'urbanisation et la construction, étaient responsables du déclin observé chez les communautés coralliennes du lagon au sud, et de l'explosion de l'algue verte Dictyosphaeria cavernosa, qui étouffe le corail, dans la partie médiane du lagon. Les coraux, dans la partie nord du lagon, demeuraient abondants et ne paraissaient pas affectés. Des pressions de la part du public et de la communauté scientifique poussèrent les autorités et l'armée à arrêter les rejets dans le sud du lagon en 1978. Maintenant, seuls des petits rejets persistent au nord. En 1983, de nouvelles observations des transects de Maragos (1972) furent réalisées avec les mêmes méthodes. Celles-ci révélent un recouvrement important en coraux, particulièrement pour Porites compressa et Montipora verrucosa dans le sud et le centre du lagon, et une abondance en coraux toujours forte dans la partie nord. Des espèces coralliennes de moindre importance, Pocillopora damicornis et Cyphastrea ocellina, sont également abondantes dans le lagon. Par contre, Dictyosphaeria a fortement décliné, à l'exception d'un léger accroissement dans la partie nord. Cette étude ainsi que des observations récentes corroborent le fait que les rejets constituaient un stress majeur pour les coraux du lagon, et stimulaient la croissance de Dictyosphaeria. De plus, ces études indiquent que les effets nuisibles des rejets sur les coraux sont généralement amplifiés en milieu confinés, avec peu de circulation.

INTRODUCTION

This study documents the response of lagoon reef coral populations in Kaneohe Bay to the reduction of sewage discharge into the bay by comparing the abundance and distribution of corals before and after sewage removal. The original data were collected in 1970-71 at 16 lagoon stations. In late 1977 to mid 1978, the two major point sources of sewage discharge into the lagoon were eliminated. In 1983 we resurveyed coral populations at the same lagoon stations using the same techniques.

Kaneohe Bay, located on the windward northeast coast of Oahu, is Hawaii's largest embayment, stretching 13 km along the coast. A large 4 km-long barrier reef occurs 1-2 km offshore from the center of the bay. The barrier and adjacent fringing reefs protect the lagoon from wave action and restrict water circulation and exchange, especially in the isolated southern end of the lagoon (Figure 1). The barrier reef is deeper in the north end of the bay, contributing to more vigorous wave action and water circulation there. As a consequence the lagoon can be divided into three physiographic sectors: the northwest semi-exposed, the central, and the isolated southeast sectors. The whole system of lagoon waters and associated reefs in the bay is unique to Hawaii.

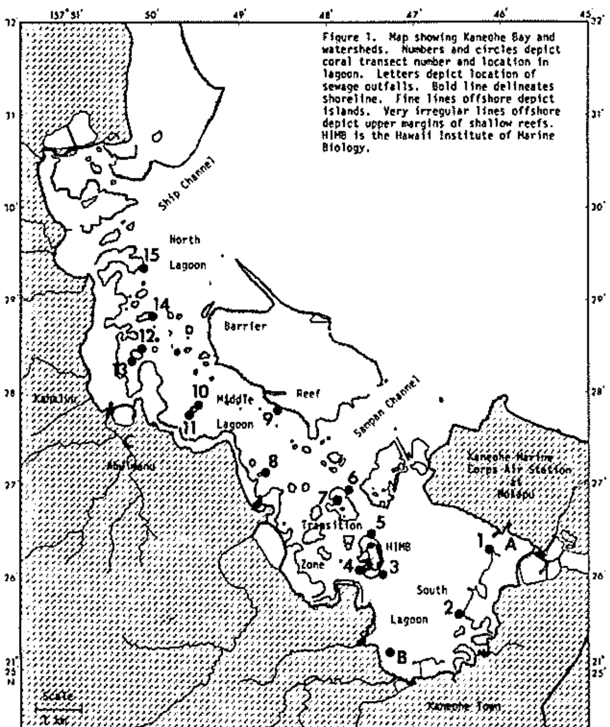


Figure 1. Map showing Kaneohe Bay and watersheds. Numbers and circles depict coral transect number and location in lagoon. Letters depict location of sewage outfalls. Bold line delineates shoreline. Fine lines offshore depict islands. Very irregular lines offshore depict upper margins of shallow reefs. HIMB is the Hawaii Institute of Marine Biology.

Kaneohe Bay has been extensively studied because of the presence of the Hawaii Institute of Marine Biology since 1951 at Coconut Island in the southern lagoon. Prolific coral communities have developed in the protected lagoon, especially on the steep lagoon slopes and shallow outer margins of the barrier, patch, and fringing reefs. Although most reef coral species reported from Hawaii are found in Kaneohe Bay, only a few species dominate lagoon habitats, with the finger coral Porites compressa comprising over 80% of the total live coral cover (Maragos, 1972). The only other abundant species is Montipora verrucosa. Other common species include Pocillopora damicornis, Pavona varians, Cyphastrea ocellina, Fungia scutaria, and Montipora patula. About a dozen other coral species have been reported from the lagoon, including a soft coral Zoanthus pacifica and the ahermatypic coral Tubastraea coccinea.

HISTORICAL BACKGROUND

Prior to western contact, the Hawaiian population in the Kaneohe watershed was principally involved with taro and fish culture (Devaney et al 1976). The bay waters were regularly fished, and over 30 rock-walled fishponds managed along the inner reef and mud flats. The 19th century saw the decline of the Hawaiian culture and the development of ranching and large-scale agriculture in the bay, including rice, pineapple and sugarcane. However, by the end of the century, much of the bay watershed had reverted back to small scale farming, rangeland, and rural use.

Beginning in 1938, the bay underwent major changes to accommodate military and residential development, especially in the south. A major decade-long military dredging and filling operation, concentrating on lagoon reefs, resulted in expansion of land area and the construction of a military air station at the southern headland of the bay (Mokapu); clearing of reefs and other hazards in the south lagoon to establish a seaplane runway; and dredging of a ship navigation channel from the south lagoon to the north end of the bay. Dredged materials not used for land-filling were dumped back into the lagoon. The 1940's ushered in an era of major residential development in the southern bay with rural lands cleared and many fishponds filled for housing tracts. By 1960, completion of two new highways linked Kaneohe to the city of Honolulu and accelerated urbanization. The land disturbance caused soil erosion and sedimentation from stream runoff during periods of heavy rainfall. Much of the sediment settled in the deep lagoon (Roy, 1970). Between 1920 and 1980, the population of the bay grew from less than 5,000 to over 60,000.

Sewage discharges into the lagoon increased in response to population growth. The Marine Corps Air Station at Mokapu began to discharge partially treated sewage into the south lagoon in 1951 (Site "A," fig. 1). In 1963 a City and County municipal outfall began discharging secondary treated sewage into the south lagoon (Site "B," fig. 1). A smaller secondary sewage treatment plant and outfall was established at Ahuimanu in 1970 to service the light rural and residential population of the north bay (Site "C," fig. 1). This sewage entered Ahuimanu Stream and eventually the northern lagoon waters of the bay. By 1977 the combined effluents of the three sewage plants and outfalls totalled over 7.5 million gallons per day (20,000 m^3/day), with 95% being discharged into the south lagoon (Smith et al., 1981).

In the late 1960's marine scientists became alarmed at the deteriorating condition of the lagoon's coral communities and suspected dredging and filling, sewage pollution, and sedimentation from urbanization to be the major causes (Roy, 1970; Banner and Bailey, 1970; Maragos, 1972; Smith et al. (eds), 1973; Maragos, 1974; Banner, 1974; Devaney et al. 1976, and Hollett, 1977). In 1968, Maragos initiated coral growth and mortality studies using transplanted corals to monitor response to bay environmental conditions. At each of 25 lagoon and outer bay transplant stations, he conducted transect quadrat surveys in 1971 to estimate abundance and distribution of reef coral populations. The scientific community collectively blamed the decline of corals in the south bay on pollution from dredging and urbanization, and implicated sewage as stimulating the growth of a green alga (Dictyosphaeria) that was smothering corals in other parts of the lagoon. However, there were never any adequate baseline surveys of reef coral populations in the lagoon prior to bay dredging and filling operations, sedimentation, and sewage pollution, and the decline of coral populations was never really documented.

Nevertheless, considerable public concern over the welfare of the bay led the county and federal governments to remove sewage discharges from the south lagoon, and by mid 1978 both major sources were completely diverted to a deep ocean outfall outside the bay. Smith et al. (1981), anticipating the diversion project, studied and monitored bay ecosystem response by measuring physical, chemical, geological and biological characteristics before and after actual sewage diversion. Although this study succeeded in documenting the short term bay response to sewage diversion, it was not specifically designed to monitor reef coral populations and the one year post-diversion phase of the study was insufficient to document the post-diversion response of lagoon reef coral populations. Corals typically respond more slowly than other organisms.

In 1983, a summer course on coral reefs was held at the Hawaii Institute of Marine Biology and allowed us to collaborate on a resurvey of the lagoon transect sites of Maragos (1972). Since our resurvey was 5-6 years after diversion of sewage from the south lagoon, we felt this interval was sufficient to document changes, if any, to reef coral populations attributed to reduction of sewage. Hence we resurveyed the same sites of the earlier study to document the more recent condition of reef corals and to compare the results to the earlier survey results accomplished at the same sites 6 years before sewage diversion.

METHODS

The 15 transect surveys accomplished by Maragos in 1971 on the lagoon slopes were resurveyed by us (Figure 1). An additional station (#8 on Figure 1) located in the middle lagoon and originally surveyed by Paul Jokiel in late 1970 was also resurveyed because the same survey technique was originally used. During the earlier study, notes on location were recorded. Also markers were left at the Maragos transects consisting of the original coral transplant platforms. Once over each site, Maragos used snorkeling gear to relocate the platforms and properly positioned the transect lines.

At several sites the original platforms could not be located because they had moved (#5), become overgrown with live coral (#6), were buried under natural accumulations of reef sediment (#7) or were not present (#8, #14). However, from memory and notes, Maragos was able to position all but one of the resurvey transects to within one to five meters of the original alignments. At only one site (#6 on Figure 1), the original survey site could not be accurately relocated because coral growth within the 12-year interval was so prolific as to obliterate previous bathymetric features and the 'seascape' as it was remembered. We estimate that the resurveyed site was still within 50m of the original survey site. In any case it was not possible to exactly replicate the earlier transect studies at any of the stations.

In addition to data variation attributed to changes in the coral populations over time, the inability of replicating the earlier alignments introduces data variation attributed to spatial changes in abundance and distribution of corals over small distances on a reef. To estimate the magnitude of this variation (or "error") and compare it to the magnitude of variation attributed to the time factor, we accomplished two transects at each of 15 stations during our 1983 resurveys. The transects were aligned parallel to one another separated by a distance of 3-5 m. Data obtained from the "replicate" transects at each station were later compared to one another in addition to the comparisons between stations.

The survey data were collected using the contiguous quadrat method originally followed by Maragos (1972). At each station, SCUBA assisted divers laid out a 25 m long transect line from the top to the bottom of the reef slope, perpendicular to the depth contours. At all stations except #6, the line was long enough to encompass the entire coral community on the reef slope with the deep end of the line on the muddy lagoon floor (devoid of coral) and the shallow end on the reef flat where coral growth is normally less developed. At station number six, 29 quadrats were required, and at least 20 quadrats were accomplished at all stations.

A one metre square quadrat frame divided with wires into a grid of 100 squares of equal area and centered over the bottom end of the transect line. The diver then recorded on underwater writing tablet the coral species, other bottom types (sand, mud, rubble, dead coral, coralline algae), *Dictyosphaeria cavernosa*, or other algae under each square. The minimum "resolution" of this technique was half a grid square (50 cm^2). Species less than this size were noted as being "present." Data on depth and slope angle were also recorded for each quadrat. After completing the census for the first quadrat position on the line, the quadrat frame was then flipped over to the next position on the line, and the census repeated until the quadrat survey reached the top of the line. This approach enabled a top-to-bottom profile of the reef slope one metre wide to be surveyed for each transect.

The raw data from the transects were later transcribed and converted to percent cover estimates for each species of coral or algae enumerated in the quadrat. Later the quadrat data were pooled to give percent live cover and distribution estimates for each species reported on the transect.

RESULTS

The raw data from the 1970-71 and 1983 surveys are presented in Table 1 for each station. Transect data on total live coral and *Dictyosphaeria* coverage plotted against depth are summarized by region (north, middle, and south bay) in Figure 2. A transition zone region was added as a subdivision of the middle bay region which includes the four mid bay transect stations closest to the south region. The transition "zone" encompasses the lagoon sector immediately south of the barrier reef but within the influence of enhanced water circulation near the Sampan Channel and south lagoon waters moving north past Coconut Island. Transect Stations 1-3 constituted the south bay sites, Stations 4-7 the transition zone sites, Stations 8-11 the mid bay sites, and Stations 12-15 the north bay sites. A fourth south bay station (located adjacent to Kaneohe Municipal outfall "A" on Figure 1) was covered with sediment and no living corals or *Dictyosphaeria* was reported during either the 1971 or 1983 survey. Table 1 presents distributional data for individual species of corals encountered during the surveys, and Figure 3 summarizes for the bay as a whole the changes in abundance of *Dictyosphaeria* and live corals between the earlier and later surveys.

Space does not permit the presentation of replicate transect data plots for each of the 15 stations. However, the plotted raw data show that the variation between replicate transect data was in most cases much less than the variation between the 1971 and 1983 transect data at the same stations. This is strongly evident for plots of total live coral cover vs. depth at all except most north bay stations and Stations 4 and 6 in the transition zone. This is also evident for plots of *Dictyosphaeria* cover vs. depth at all except the south bay stations and Stations 12 and 13 in the transition zone. These results suggest that overall coral coverage in the north lagoon did not increase by 1983. Coral coverage was already high at 3 of 4 stations. Increases in coral coverage at depths less than 3m at Station 13, and Station 12, was

TABLE 1. Distribution da[illegible] species of reef corals and Dictyosphaeria encountered durin[illegible] 1971 and 1983 transect surveys at the 15 lagoon stations. [illegible]umbers indicate total times each species was encountered in the squares of the quadrat along each transect. The 1983 numbers represent the means of the replicate transect data at each station. A dash indicates the species was not present on the transect. MP = *Montipora patula*; PM = *Pocillopora meandrina*, and PS = *Psammocora stellata*.

LOCATION	SOUTH BAY			TRANSITION ZONE				MIDDLE BAY				NORTH BAY				TOTALS
STATION NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
SPECIES																
Porites compressa																
1971	-	7	16	237	50	943	15	365	129	114	376	612	29	711	564	4,168
1983	19	8	313	220	351	374	438	1,006	353	730	620	872	504	922	424	7,154
Montipora verrucosa																
1971	3	-	10	43	7	259	-	13	7	3	10	1	7	158	67	588
1983	58	22	208	78	172	138	26	19	29	26	172	4	57	18	1	1,028
Pocillopora damicornis																
1971	-	-	-	-	1	1	3	2	6	3	3	8	4	2	8	41
1983	6	6	8	12	18	30	20	32	12	34	10	100	27	9	4	328
Cyphastrea ocellina																
1971	-	-	-	-	-	-	-	1	-	1	-	-	-	-	1	3
1983	2	-	-	-	2	2	8	6	9	10	4	6	5	2	5	61
Fungia scutaria																
1971	-	-	1	-	1	-	-	14	1	12	11	14	3	3	9	69
1983	-	-	2	-	2	-	6	4	4	14	6	1	-	4	1	44
Pavona varians																
1971	-	-	-	-	-	-	-	1	1	4	-	-	-	-	-	6
1983	-	-	-	-	-	2	-	1	1	-	32	-	-	-	-	36
Other Corals																
1971	-	-	-	-	-	3(MP)	-	-	2(MP)	-	3(MP)	3(MP)	-	5(MP)	1(PS)	17
1983	-	-	-	-	-	1(PM)	-	1(PS)	-	-	2(MP)	-	-	-	1(PS)	5
Dictyosphaeria cavernosa																
1971	-	-	-	520	327	448	907	240	991	610	630	3	-	25	134	4,835
1983	3	-	1	51	84	48	76	225	74	160	40	10	118	30	326	1,246

attributed to rapid recovery from a freshwater coral kill in 1965 (see Holthus *et al*. 1985). However, the kill did not contribute to coral declines at the other 1971 transect stations. A slight decrease in coral coverage at Station 15 in the north bay may have been the result of recent encroachment by *Dictyosphaeria* which increased dramatically at the site since 1971.

Dictyosphaeria was nearly absent in both the 1971 and 1983 surveys in the south bay. As noted earlier, coral surveys in 1983 at Station 6 probably involved a different population compared to the 1971 survey, and the bathymetry at the 1983 site was much different from the 1971 site. This could explain the anomalous minor "decline" in coral coverage at Station 6. Although coral coverage in shallow depth at Station 4 did not increase over time, the deep water populations did increase markedly in coverage.

Total live coral coverage in the lagoon as a whole increased dramatically between 1971 and 1983, almost doubling in abundance (Table 1; Figure 3). Live coral coverage was substantially higher in 1983 at all depths at south, transition, and middle bay regions compared to 1971 levels. The abundance of coral in 1983 at the mid bay stations had nearly approached the highest levels in the lagoon reported in the north lagoon. The transition zone and particularly the south lagoon coral populations did not yet reach the high abundance levels reported more to the north. Despite spectacular increases in south lagoon coral communities and the presence of many small colonies by 1983, overall abundance is still only a fraction of those of other regions and it may take decades for the communities to recover completely (Figure 2). Notable coral recovery on old dredged surfaces was also reported at Station 2 and observed elesewhere in the south lagoon. In contrast, coral recovery on deteriorated reef surfaces covered with sediment had not yet begun at one south bay station.

In 1971, *Dictyosphaeria* was more common in the lagoon than any single coral species and its abundance was equivalent to all coral species combined (Table 2). However, by 1983 *Dictyosphaeria* showed dramatic declines in coverage at most bay stations with its recent overall level being only 25% of its earlier level (Table 1; Figure 3). Spectacular decreases were reported at all transition and mid bay stations where *Dictyosphaeria* had earlier exhibited its peak abundance (Figure 2). *Dictyosphaeria* declines in deeper water appeared to be larger than declines in shallow water (Figures 2, 3; Table 1). Although *Dictyosphaeria* continues to be nearly absent in the south bay, it showed a moderate increase in most north bay stations (Table 1, Figure 2) in 1983 compared to 1971 levels. Interestingly, the alga showed a dramatic increase at Station 13, the north bay station closest to the Ahuimanu Sewage outfall which was still discharging sewage at the time of the 1983 survey.

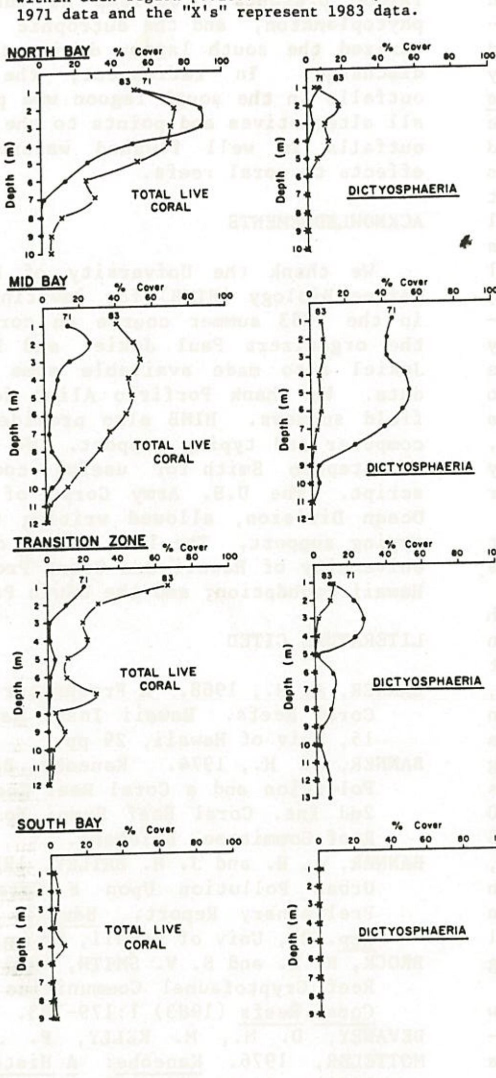
Dramatic increases in the abundance and distribution of individual species of corals were also reported (Table 1). The most abundant species *Porites compressa* nearly doubled its abundance since 1971 and reported major increases at all stations except two (#4 and #15; Table 1). *Porites* was completely absent at Station 1 in 1971 but present in 1983. The growth of *Porites* was so impressive at some stations (10-13) that the platforms were heavily colonized and nearly hidden by coral growth. Up to 50 cm of growth was reported over the platform at Station 12 and the platform could not be relocated at all at Station 6 where coral growth was suspected to have covered it. Likewise *Montipora verrucosa* nearly doubled its overall abundance in the lagoon showing increases at 12 of the 15 stations (Table 1). The species was absent from Stations 2 and 7 in 1971 but present at those stations in 1983.

Several of the less common species reported at the stations showed remarkable increases in their distribution and abundance (Table 1). Although *Pocillopora damicornis* was absent from all south bay and one transition zone stations in 1971, it was present at 15 stations and showed increased abundance at 14 stations. A similar but more impressive trend was recorded for *Cyphastrea ocellina* (Table 1). During the 1971 survey, the species was reported at only 3 stations (2 middle bay and one north bay station). By 1983 *Cyphastrea* was reported at 12 lagoon stations and showed increased abundance at all of these stations. It was absent only at three south bay and one transitions zone station. In contrast, the soft coral *Zoanthus pacifica* was observed to be present at all south bay, one transition and one mid bay station in 1971 but was absent at all stations during the 1983 survey. The other rarer species of corals were not encountered often enough during the transect surveys to demonstrate any obvious trends over time.

DISCUSSION

The study of Smith *et al*. (1981) is the only other to document ecological conditions in Kaneohe both before and after the cessation of sewage discharges in

Figure 2. Live coverage of coral and *Dictyosphaeria* in 1971 and 1983 plotted against depth for four regions in Kaneohe lagoon. Data from all stations within each region pooled. The dots represent 1971 data and the "X's" represent 1983 data.



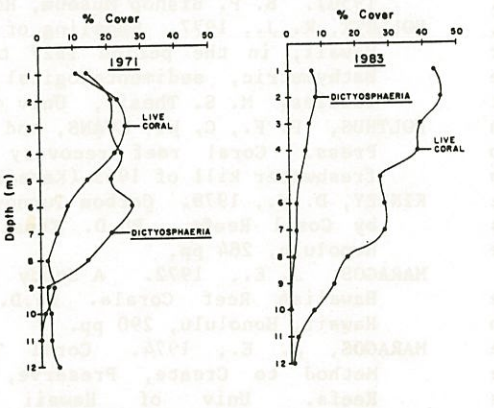


Figure 3. Live coverage of coral and *Dictyosphaeria* in 1971 and 1983 plotted against depth. Data from all stations pooled.

the south lagoon. They viewed the bay as a single nutrient subsidized ecosystem prior to diversion and placed emphasis on monitoring biomass and productivity of major organism groups rather than the progress of individual species. They documented a rapid decline in phytoplankton, zooplankton and benthos (primarily suspension feeders) in the south bay and a decline in *Dictyosphaeria* in the middle bay following diversion and the elimination of sewage nutrient subsidy. Brock and Smith (1983) monitored cryptofaunal communities on reefs before and after diversion and noted increased biomass of hard-bottomed cryptofaunal communities during sewage loading and declines after diversion. Nevertheless the study was not able to document recovery by reef corals.

Our study documented an essentially opposite pattern and rate of response by reef coral communities. Coral populations were at depressed levels in the south to middle lagoon before diversion. Although responding slowly at first to the termination of sewage, reef corals are now dramatically recovering their abundance, distribution, and diversity throughout all regions of the lagoon previously affected. Surprisingly these responses were not limited merely to south lagoon corals earlier affected directly by sewage or transition and middle bay coral populations, primarily *Porites* and *Montipora*, that were previously affected by massive growths of *Dictyosphaeria*. Even some less common coral species including *Pocillopora* and *Cyphastrea* showed substantial increases in abundance and distribution throughout the entire lagoon. Although it is difficult to explain how the termination of sewage discharges could stimulate measurable coral recovery up to 10 km to the north, the exhibited patterns of coral recovery cannot be dismissed as a coincidence nor are other explanations for the recovery plausible. Some of the coral species responding to the reduction of sewage stress may serve as extremely sensitive indicators of sewage pollution.

Our 1983 documentation of *Dictyosphaeria* declines are consistent with the earlier measurements of Smith *et al*. (1981). We determined that the algae declined to one fourth of its prediversion abundance overall and noted major population collapses at seven out of the eight stations in the transition and middle lagoon regions. The rapid decline following diversion suggests that *Dictyosphaeria* was previously stimulated by nutrient subsidies from the sewage. The initiation of sewage discharges in the north bay from the Ahuimanu Sewage Treatment well as the moderate increases in *Dictyosphaeria* coverage we observed along the north bay transects.

The continued absence of *Dictyosphaeria* from the south lagoon is more difficult to explain. Smith *et al*. (1981) concluded that the algae's growth was limited by light due to reduced light penetration in the water column from suspended particulates. However, Maragos (1972) reported huge populations of the algae in deeper water (to 9-11 m) during the mid bay and transition zone transect surveys in 1971 and during qualitative observations in the bay between 1970-74, and was constantly removing growths of the algae from his deeper platforms to prevent the algae from smothering the coral transplants. Our 1983 surveys show that most of the *Dictyosphaeria* decline occurred on the deeper portion of the reef slope (see Figures 2, 3) during a time interval when light penetration was expected to increase. Nutrient limitation seems to be more important than light limitation to explain the decline of the algae on mid lagoon reef slopes, and it may be partly responsible for its continued absence in the south lagoon. The small amount of the algae reported in the south bay before diversion declined after sewage diversion. Also substratum instability on the steeper deteriorated reef slopes (see Kinsey, 1979) and residual toxicity of the bottom sediments in the south lagoon from previous sewage discharges may render bottom habitats there inhospitable to *Dictyosphaeria* colonization.

It is difficult to distinguish the negative effects of sedimentation from that of sewage discharges since both were concentrated in the south bay during the same time, and since coral recovery has occurred during a period when both of these stresses have been substantially reduced. The shoaling of the lagoon floor reported by Roy (1970) and not disputed by Hollett (1977) probably buried corals at the base of the reef slopes, but the effects of suspended sediments are more difficult to estimate. Dredging, filling, and soil erosion and runoff all generated suspended sediment but there has been little documented impact on corals. Maragos (1972) recorded exposure of transplanted corals to episodes of heavy suspended sediment, and a few colonies of Pocillopora at one north bay station (#13) succumbed although the dominant resident species (Porites compressa and Montipora verrucosa) survived. Transplanted corals also died consistently at one south bay station but this was located adjacent to the municipal outfall ("B" on Figure 1). Maragos was able to demonstrate a stronger statistical correlation between the coral mortality (particularly Porites compressa) and sewage, especially at south bay stations without obvious sedimentation. The dominant species of coral in the bay appears to be very sensitive to sewage and more resistant to sedimentation which would tend to diminish the significance of suspended sediments as a cause of the major decline of corals in the south bay. Elsewhere in the lagoon sedimentation has been only a minor factor in the decline except near the floor of the lagoon.

Our 1983 south bay transect results suggest that sewage discharges had prevented or inhibited the recolonization of corals on dredged surfaces at or near survey sites (especially station 2) in the south lagoon. Our recent studies indicate corals have begun to rapidly recolonize dredged surfaces there now that sewage has been diverted. Furthermore, Maragos (1972, 1974) earlier observed greater coral recovery on dredged surfaces outside of the south lagoon. The more recent estimates of military dredging and filling by (see Devaney et al 1976) indicate that 110 hectares of reefs were filled at Mokapu and over 11,000,000 cubic metres of reef material was dredged between 1938 and 1945, most of this in the south lagoon. However, coral populations in the south lagoon may have been destined for major decline by sewage stress, even in the absence of the earlier massive dredge and fill operations, based upon coral mortality during transplant studies between 1969 and 1974.

Recent increases in corals reported at shallow depth at two north bay stations were in part attributed to coral recolonization on reefs damaged by a major freshwater flood of 1965 (Holthus et al. 1985). In 1971, coral abundance on the slopes, as a whole, was higher in shallow water compared to deeper water (Figures 2, 3). This is opposite from what would be expected from coral communities killed by the buoyant freshwater plumes from the flood. Although corals on reef flats were severely damaged by the flood to depths of 1.5m (see Banner, 1968), coral population levels on the reef flats are much lower than on the slopes. Thus, the rise and fall of sewage discharges is the only plausible explanation for most of the decline and recent recovery of lagoon reef corals.

In retrospect, the earlier decision to eliminate sewage discharges from the south lagoon resulted in major benefit to reef coral populations in Kaneohe lagoon. A similar diversion of the Ahuimanu sewage should result in additional recovery of reef corals and benefit to the reef ecosystem in the bay. Equally important is the fact that the diversion of this sewage to a deep ocean outfall offshore from Mokapu Peninsula and outside the bay has not resulted in noticeable adverse impact to the exposed reef communities adjacent to the outfall.

At first it may pose as an enigma that a comparable amount of sewage that caused catastrophic damage to corals inside the bay would have only negligible impact to reefs outside the bay. The ocean outfall site is exposed to strong currents, waves, and water circulation and residence times are measured on the order of hours. In contrast, the south lagoon of Kaneohe Bay has poor flushing with residence times measured on the order of weeks (see Smith et al, 1981). The rapid turnover of waters outside the lagoon prevents a buildup of nutrients, biomass of phytoplankton, and the eutrophic waters that characterized the south lagoon during the period of sewage discharge. In retrospect, the location of the outfalls in the south lagoon was perhaps the worst of all alternatives and points to the need to site sewage outfalls in well flushed waters to avoid adverse effects to coral reefs.

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COASTAL RESOURCE INVENTORIES IN HAWAII, SAMOA AND MICRONESIA

INVENTAIRES DES RESSOURCES COTIERES AUX HAWAI, AUX SAMOA ET EN MICRONESIE

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ABSTRACT

Since 1978 the Corps of Engineers has sponsored coastal resource and coral reef inventories in Pacific areas which are under U.S. jurisdiction. Completed inventories in Hawaii include the islands of Oahu, Maui, West Hawaii, and Kauai, with Molokai in progress. The inventory in American Samoa covered the islands of Tutuila, Aunu'u, Ofu, Olosega and Ta'u. In the Caroline Islands an inventory was completed for Moen (in Truk); one is in progress for Pohnpei and one is planned for Kosrae.

The inventory products include a report correlated with an atlas of large scale maps. The products are designed for use by scientists, planners and other officials with management responsibilities over coastal resources. Field data collection emphasizes marine biology (fishes, corals, algae, etc.), oceanography, water quality and marine geology. Other data sources include aerial photographs, literature reviews and interviews with knowledgeable scientists, officials, fishermen and other resource users. The photographs also play a key role in map preparation.

The narrative report describes the marine and terrestrial ecology, geomorphology, cultural resources, water quality and oceanography, human uses and other topics for each geographic reach of an island or reef. The geographic coverage of each atlas map corresponds to that of the respective report narrative and includes data on bottom types, bathymetry, currents, waves, study sites and human uses or values plotted by "use" symbols. Reliance on remote sensing and extensive field techniques allows large remote areas to be mapped rapidly.

A major value of the inventories is the completed geographic description of important coastal resources in a format that allows managers to direct development away from valuable reefs and other resources worthy of protection. The inventories also identify sites worthy of more intensive research and management and provide "baseline" data to develop resource conservation plans, such as the one in progress for Pohnpei (Holthus, this volume).

RESUME

Depuis 1978, le Corps des Ingénieurs a favorisé le développement d'inventaires des ressources côtières et des récifs coralliens dans des zones du Pacifique étant sans la juridiction des Etats Unis. Des inventaires complets ont été faits à Hawaii dans les îles d'Oahu, Maui, Hawaii ouest et Kauai et se poursuivent à Molokai. Dans les Samoa américaines, l'inventaire couvre les îles de Tutuila, Aun'u, Ofu, Olosega et Ta'u. Dans les îles Carolines, un inventaire a été achevé à Moen (à Truck); un est en cours à Pohnpei et un en projet pour Kosrae.

Les inventaires comprennent un rapport correspondant à un atlas de cartes à grande échelle. Ils sont destinés aux Scientifiques, aux planificateurs et aux instances officielles ayant des responsabilités dans l'aménagement des ressources côtières. Les données de terrain portent surtout sur la biologie (poissons, coraux, algues, etc), l'océanographie, la qualité de l'eau et la géologie marine. Les autres sources de données incluent des photographies aériennes, des revues bibliographiques et des interviews de scientifiques bien informés, d'officiels, de pêcheurs et d'autres utilisateurs de ces ressources. Les photographies jouent également un rôle important dans la préparation des cartes.

Le rapport décrit l'écologie marine et terrestre, la géomorphologie, les ressources culturelles, la qualité de l'eau et l'océanographie, les utilisations humaines et d'autres sujets pour chaque point géographique d'une île ou d'un récif. La couverture géographique de chaque carte de l'atlas correspond à celle d'un rapport particulier et inclue des données désignées par des symboles sur les types de fond, la bathymétrie, les courants, les vagues, les sites étudiés et les utilisations humaines. La confiance en des connaissances séparées et en des techniques de terrain extensives permet de cartographier rapidement de larges zones éloignées.

Un intérêt majeur de ces inventaires réside dans la description géographique complète de ressources côtières importantes dans un format qui permet aux aménageurs d'orienter le développement loin des récifs florissants et des autres ressources qui doivent être protégées. Les inventaires identifient aussi les sites qui nécessitent des recherches et des aménagements plus intensifs et offrent une base de données pour développer des plans pour la conservation des ressources comme celui qui est en cours à Pohnpei (voir Holthus).

INTRODUCTION

This report describes an ongoing program to collect and present information in a way that facilitates the designing and siting of development and other activities to avoid significant impacts to coastal resources. The emphasis of our studies to date has been on selected coral reefs in the tropical Pacific under United States jurisdiction. Scientific data are scarce and frequently not in a form useful to the majority of decisionmakers, especially those lacking scientific backgrounds. Furthermore, University-level research institutions are located only in Hawaii and Guam, rendering most of the region remote from scientists. Nevertheless, the scale and rate of development in the U.S. tropical Pacific suggest that many decisions will continue to be made in the future, whether or not important information is available or whether communication with scientists and others knowledgeable about the resources is accomplished. Although the indigenous Pacific cultures harbor a wealth of valuable information on the characteristics and conservation of coastal resources (see Johannes, 1978), scientists are often in the best position to synthesize information from a variety of sources and offer written or verbal advice on resource conservation. Islands with coral reefs and related coastal ecosystems presently under U.S jurisdiction in the Pacific include Hawaii, American Samoa, Mariana Islands, Marshall Islands, Caroline Islands, selected atolls and islands in the Line Islands, and several other isolated islands and atolls.

MOTIVATION FOR THE RESOURCE INVENTORIES

The present economic status and population distribution is largely the result of influence and control over the islands during the past one to four centuries by Spain, Germany, Japan, and the United States. This collective influence has led to the gradual conversion of many traditional subsistence values and lifestyles in the islands to those espousing "western" concepts such as a cash economy, private land ownership, large scale agriculture, military and industrial development, urbanization, and government service and employment.

The Pacific theatre of World War II and military construction before and after the war caused considerable physical and cultural changes in most of the islands, and resulted in major impacts to coral reef ecosystems. Extensive destruction from dredging and filling for military bases and facilities occurred in Hawaii, Marianas, Carolines, and the isolated atolls of Palmyra, Johnston, Wake, and Midway. Nuclear weapons testing, missile testing, and associated construction after the war caused additional degradation of reefs, especially at Bikini, Enewetak, and Kwajalein in the Marshalls, Johnston Atoll, and other atolls (Canton, Christmas).

After the war years, major improvements in sanitation, nutrition, and medical services contributed to rapid population growth and consequent greater demands upon all island resources. Many island societies under U.S. control lack economic development and are still dependent upon subsistence resources. In recent years major dredging, filling, and construction for public works projects, especially airfields, ports, roads, and landfill sites for urban development has adversely affected many coral reefs and mangroves throughout all of the major island groups. The reefs in most areas are now looked upon as "free" resources open to development: subject to dredging to obtain construction aggregate, and attractive for landfilling to expand the land areas of small islands. Additional population growth and "urban drift" has been caused by the migration of people from the outer islands to the district centers in search of jobs and better living conditions. This shift has placed greater demands upon the limited land and coastal resources especially in the Marshalls and Carolines. The attendant increase in pollution, sedimentation, dredging and filling has degraded lagoons, estuaries, mangroves, and coral reefs, further depressing the ability of these resources to sustain the growing populations.

We initiated the coastal resource inventory program with the goal of providing basic information in a manner that will facilitate resource management and the development of conservation programs. We have emphasized presentation of important information in a form that will be understood and used by planners and decisionmakers in the event that scientific advisors are not available.

DATA SOURCES

The inventories have relied upon a full range of data including: 1) unpublished and published literature, 2) interviews with scientists, fishermen, officials, and others knowledgeable of the resources; 3) field surveys techniques that are semi-quantitative but extensive in coverage; and 4) interpretation of remotely sensed data, especially medium and low altitude aerial photographs. For island inventories outside Hawaii, the literature is not extensive. Interviews have been particularly valuable for providing information on past, present, and future uses, demands for resources, pollution problems, fishing areas, development proposals, valuable ecological and research sites, and conservation practices and controls.

We have relied heavily upon interpretation of aerial photographs to map cover types, bottom types, land use, wetlands, coral reef biotypes, oceanographic features (including wave breaks), and geomorphology. Access to remotely sensed data allows field surveys to be designed more effectively, and reduces the time, cost, and logistical problems associated with field surveys at remote or inaccessible coastlines and islands. Natural color aerial photographs have demonstrated excellent depth penetration in coastal waters, and we have been able to map submarine features to a maximum depth of 20m in the more transparent waters. False-color or near-infrared imagery has facilitated interpretation of terrestrial and wetland features especially vegetation, but depth penetration in water is limited to less than 2m. Often black and white aerial photographs are the only imagery available, but these can provide a wealth of information and allow accurate mapping of coastal resources. These Photographs have also served as convenient and economic mapping bases during preparation of some of the atlases.

Field surveys are to cover large coastal areas during limited field time. Using scuba diving or snorkeling gear, the survey team typically samples a number of different habitats during "spot" surveys, each of short duration and which avoid the use of transects, quadrats or other time-consuming techniques. Sometimes, divers are towed behind boats using a portable sled to extend underwater observations over larger areas. At each stationary site, divers equipped with cameras and note pads record the abundance and distribution of marine species especially those of subsistence, recreational, commercial, or ornamental value. Major organism groups of interest include fish, corals, algae, other invertebrates, sea turtles, and marine mammals, and the abundance of each species is assigned one of 5 categories (rare, uncommon, common, abundant, and dominant). Also, attempts are made to estimate the number or size of edible species.

At each site observations are made on other existing or potential uses or activities including fishing, surfing, sailing, discharges, dredging, sport diving, research, aquaculture, etc. Observations on water quality, currents, wave action, and geomorphology, shoreline erosion, archaeological and historic sites, and land use and vegetation landward of the shoreline is also recorded. The field surveys also serve as "ground truth" verification for aerial photographic interpretation of submarine bottom types and coastal features.

DATA COMPILATION

The final products of each inventory are a narrative report (or text) and an accompanying atlas. Data compilation is different for each of these two products. The narrative report includes: a general summary and analysis of the methods and findings; and a description of each section of the shoreline and reef around the island. Collected data are summarized and compiled in a form so that each coastal section can be described as a complete unit. The narrative report is more analytical and provides information on previous studies and estimates of the abundance and distribution of important species or resources.

The atlas consists of a series of maps with the geographic coverage of each corresponding to that of the descriptive sections in the companion narrative report. The maps are prepared at a scale of 1:6,000 to 1:25,000 and include information on the distribution of coastal resources and their uses, values, and functions to man. Maps published by the U.S. Geological Survey or the National Ocean Survey or aerial photographs of appropriate quality and coverage serve as mapping bases for the atlas maps. Where published maps serve as the base maps, imagery detail is transferred from aerial photographs to the maps using optical overlay techniques. We now use the stereo zoom transfer scope of Bausch and Lomb which enables transfer of details between maps and photographs of different scale, orientation, and distortion. When the aerial photographs serve as the basis for the atlas maps, half tone copies of the photographs are reproduced with lines, symbols, numbers, letters, and phrases, etc. superimposed. In one case, (the west Hawaii atlas) mosaics using adjacent aerial photographs were prepared to serve as the mapping base, but this process is time consuming and requires that the photographs have little distortion and exhibit consistency in shade and tonal contrast.

The uses, values, and important functions of coastal resources in each geographical sector are expressed on each map using a set of "use" symbols. Different symbols have been developed for each "use" category including: various fishing techniques, sailing, trolling, canoeing, power boating, sportdiving, seaweed collecting, shellfish gathering, ornamental shell and fish collecting, etc. Also, depicted on the maps are the locations of ports, aids to navigation, the locations of earlier study and recent inventory survey sites, and selected bathymetry.

RESULTS: STATUS OF THE INVENTORIES

The coastal resource inventory studies were initiated in 1978. For Hawaii, texts and atlases have been completed for the islands of Oahu (Aecos, Inc., 1979a, 1981), Maui (Aecos, Inc., 1979b, 1979c), the west coast of Hawaii (Nolan and Cheney, 1981; ORCA Ltd., Cheney, and Cartographic Relief, 1981) and Kauai (Aecos, Inc., 1982; Manoa Mapworks, 1983). An atlas has been completed and text is in preparation for the island of Molokai. For American Samoa a text and atlas were completed for all major inhabited islands in the territory (Aecos and Aquatic Farms, 1980; Aquatic Farms and Aecos, ND). Also a combined text and atlas was prepared for Moen Island, in Truk lagoon (Cheney et al, 1982). A text and atlas are in preparation for Pohnpei (Ponape). The Army is also sponsoring a coral reef inventory project at Johnston Atoll which is a National Wildlife Refuge. Examples of completed atlas maps, including the detailed legends are provided in figures 1 and 2.

DISCUSSION AND CONCLUSIONS

There are several requirements for effective management of coastal resources, including coral reefs. These include: 1) The availability of accurate information on the abundance and distribution of important resources. 2) The availability of accurate information on resource uses, functions, values, and future demands upon the resources. 3) Establishment of a planning and decision-making process that integrates the above two factors into a full evaluation of alternatives to achieve future development and conservation objectives. 4) Placing priority attention upon those areas (especially population centers) where the resources are in greater jeopardy.

Inventory studies that concentrate merely on the collection of ecological and scientific information without including the socio-economic values of these resources (recreational, commercial, subsistence, etc.) will not be as useful to planners and decisionmakers. Likewise, the development of general or conceptual management plans to protect coastal resources without including inventory or geographic-specific data on the resources also can lead to serious shortcomings. A factor often overlooked by more general approaches is that some tropical ecosystems, particularly coral reefs, exhibit tremendous variation in structure, function, degree of development and value over short distances. Although the planning for many individual development projects usually involve the collection of baseline environment data, these studies are often limited to the immediate vicinity of the proposed project sites. Unless comparable resource information is available for other regions, the relative importance of the resources in the region to be affected to those of other regions cannot be made. On the other hand, if the geographic variability is known, planners and decisionmakers can require that potentially damaging development projects be designed and sited away from more valuable resources, and in the process, avoid potentially serious adverse impacts.

Our studies have also verified that the coral reefs near urban population centers are being degraded most severely. Because these reefs are potentially of greater socio-economic value, they deserve priority attention. As Holthus (1985) notes, several ongoing programs to develop coral reef management programs have focused on remote areas away from population centers (for example, the Great Barrier Reef and the Northwest Hawaiian Islands). These approaches are not particularly applicable to many "urban" coral reef areas in the U.S. Pacific territories. There, the decisionmakers often do not have the luxury of preventing additional development on these reefs, and the questions most often asked of them are how much development and where?

As a consequence, we have attempted to conduct and design our inventory studies in a manner to address three of the four important prerequisites for effective management. We have attempted to integrate both scientific and socio-economic (or "use") information into the texts and atlases of our studies, offering officials greater functional and geographic perspective to improve their decisions involving coral reefs and other resources. On the other hand, the inventories will not solve all development problems or fulfill all research needs. More detailed

Aerial Photograph Based Classification System

OFFSHORE

s – Sediment.
- **sc** – Sand bottom, including channels, in water depths less than 10 meters (especially common offshore from beaches)
- **sd** – Sand bottom, deeper than 10 meters (some possibility of error, such as white reflecting rock in deep water, not checked by dives)

Special types.
- **co** – Areas of greater than 50% live coral cover (spot checked for verification)
- **br** – Beachrock (offshore)

r – Rock.
- **rs** – Mostly sand bottom but with some rocky features; rock bottom covered by a veneer of sand
- **rbs** – Hard bottom, but with conspicuous sediment up to 50% coverage
- **rb** – "Other" hard bottom types (a catch-all for dark areas, not reefal or sedimentary; normally basalt with a thin veneer of marine life).
- **rbb** – Seaward extensions of boulder beaches, with definable rocks or boulders
- **rbc** – Seaward extensions of cobble beaches (rocks smaller than boulders)

rc – Reef complex.
- **rc** – Shallow reef flats or structural reefs, normally (but not exclusively) in water depths less than 2 meters.
- **rcl** – Consolidated limestone, lacking sediment (also a catch-all for moderate to high relief areas).
- **rcp** – Consolidated smooth limestone pavement
- **rcg** – Consolidated reef with well defined groove-and-spur system.
- **rsg** – Sand predominates in the depressions of conspicuous groove-and-spur system
- **rcs** – Mostly consolidated reef with some (25–50%) sediment bottom

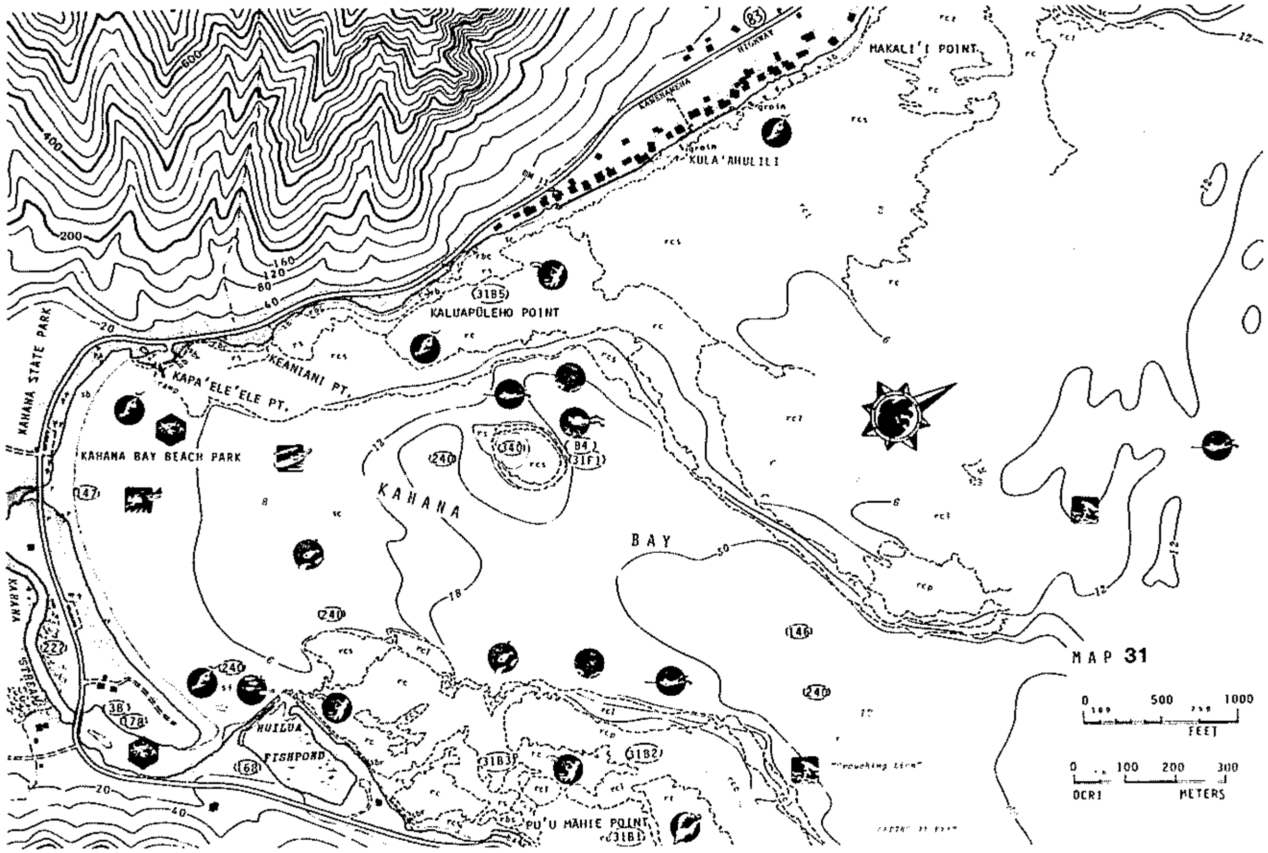

Figure 1. Coastal Resources of Kahana Bay, Oahu, Hawaii, represented on line map.

SHORELINE

ba – Volcanic rock shorelines.
- **ba1** – Low basalt outcrops/shoreline less than 1 meter high, including ramps.
- **ba2** – Talus rocks at the base of high sea cliffs (clearly not reworked by waves into a beach); sometimes this unit is seaward of ba4 or ba5 cliffs.
- **ba3** – Low outcrops to low cliffs (1–3 meters high), shoreline access possible.
- **ba4** – Sea cliffs more than 10 meters high; access difficult to dangerous.
- **ba5** – Sea cliffs more than 10 meters high; access dangerous to impossible.

bb – Man-made boulder shorelines (blue rock, revetments, rip-rap, etc.).

bc – Concrete/cement masonry seawalls and shorelines.

bd – Prehistoric walls including those of Hawaiian fishponds.

lm – Limestone rock shorelines.
- **lm1** – Low outcrops, boulders of limestone, including ramps.
- **lm2** – Limestone talus (probably rare, since limestone cliffs are not expected to be high).
- **lm3** – 1–3 meter high limestone cliffs
- **lm4** – Limestone cliffs 3–10 meters high.
- **lm5** – Limestone cliffs more than 10 meters high.

s – Sedimentary shoreline.
- **sa** – Storm beach, deposited by large waves well inland and/or above shoreline.
- **sb** – White sand beaches.
- **sb1** – Detrital sand beach.
- **sbb** – Boulder beach.
- **sbc** – Cobble, pebble beach.
- **sbr** – Poorly sorted deposits (common off stream mouths, sometimes shoreward extensions of rubble or sand beaches).

Special types.
- **br** – Beachrock (a specialized category normally formed at the shoreline).
- **tp** – Tidepools, where they are a prominent feature at the shoreline.
- **wl** – Wetland (including swamps and marshes).
- **silt** – Very fine sediments of terrigenous origin.
- ● – Fresh water spring.

Offshore Bottom Type Summary

Categories	% Sand	% Rock
rbc, br, s, sb, sc, sd	100	—
rs	less than 50	more than 50
rbs, rcs, rsg	25 — 50	50 — 75
r, rc, co	less than 25	more than 75
rbb, rb, rcl, rcp, rcg	—	100

Photograph 1–217: Section 16

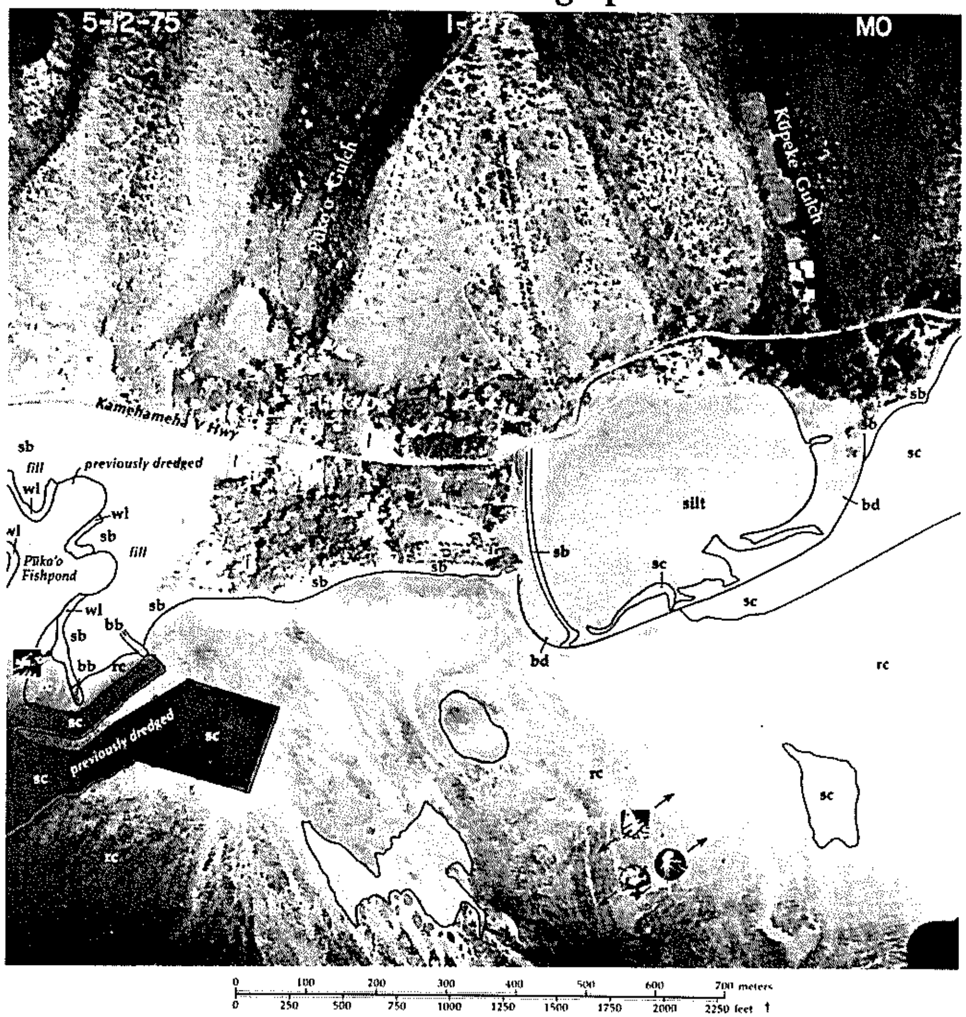

Figure 2. Coastal resources of Puko'o, Molokai, Hawaii, represented on photo map.

Uses and Activities Along and Off the Coast

USES RELATED TO NEARSHORE BIOTA

- Pole-and-line fishing.
- Gill-netting.
- Throw-netting.
- Spearfishing.
- Torching.
- Trapping.
- Lobster.
- Sea urchin (wana).
- Octopus (he'e).
- Surround netting.
- Aquarium fish collecting.
- Seaweed (limu).
- Sport-diving.
- Shell collecting.

SHORELINE AND DEEP-WATER FISHING ACTIVITIES

- Crabbing (kona, 'a'ama, swimming crab).
- Limpet (opihi).
- Trolling, bottom-fishing.
- Specialized fisheries (type indicated).

USES NOT RELATED TO BIOTA

- Board surfing.
- Body surfing / Swimming.
- Canoe paddling.
- Sailing.
- Aquatic recreation (smallcraft sailing, wind-surfing).
- Excursion boat.
- Anchorage.

Observation Sites

- Inshore (inside reef).
- Offshore (beyond reef).
- Observation routes.

† Bar scale was calculated for an average photo scale of 1:5930. Variation in flying height may create differences of up to 4.8% in scale accuracy.

information is usually required for fisheries and wastewater management, historic preservation, the design of complex or large scale development projects, etc. In these circumstances the inventory data can frequently serve as a start in the designing and location of more rigorous, intensive, and quantitative gathering of information. In many of the islands, the texts and atlases offer one of the few, if not the only meaningful source of information to guide future research and development on coral reefs. These types of inventories may also be of value to other coral reef areas in developing countries.

ACKNOWLEDGEMENTS

We are grateful to people too numerous to mention here who participated in or supported the inventory projects over the years. Nevertheless, some people devoted considerable volunteer time towards the successful completion of the reports and atlases: Eric Guinther, Paul Bartram, Daniel Cheney, George Krasnick, the late Dennis Devaney, Ron Nolan, Marine Options Program Students of the University of Hawaii, Paul Holthus, Jane Eckelman, and Everett Wingert. The inventories were funded in part by federal grants from the U.S. Office of Coastal Zone Management and in part by Section 22 of the Water Resources Development Act of 1974 as amended (Planning Assistance to States).

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION IX
75 Hawthorne Street
San Francisco, CA 94105-3901

January 21, 1993

MEMORANDUM

SUBJECT: CORAL REEF REVIEW PAPER

FROM: Brian D. Melzian Brian
Regional Oceanographer
Region IX

TO: ADDRESSEES

During my trip last week to Honolulu to represent Region IX at the "Pacific Regional Research Board" meeting, I met with Dr. Steve Dollar who works at the Hawaii Institute of Marine Biology, University of Hawaii. In 1989, Dr. Dollar was hired by EPA to conduct a coral community survey in the vicinity of two sugar cane mill discharge points located on the northeast coast of the Island of Hawaii.

During my meeting with Dr. Dollar, he gave to me a copy of the attached paper entitled NATURAL AND ANTHROPOGENIC DISTURBANCE ON CORAL REEFS (Grigg and Dollar, 1990). Because of your past and present work or interest in coral reef ecology, I thought that you would like to have a copy to this paper. Please see me if you have any questions. Thanks!

Attachment (1)

ADDRESSEES:
Pat Cotter (W-7)
Dave Stuart (W-7)
Norm Lovelace/Pat Young (E-4)
Jacques Landy (W-5)
Bill Pierce (W-5)

Reprinted from: *Coral Reefs*, ed. by Z. Dubinsky

Chapter 17

NATURAL AND ANTHROPOGENIC DISTURBANCE ON CORAL REEFS

RICHARD W. GRIGG and STEVEN J. DOLLAR

INTRODUCTION

Coral reefs have often been described as fragile ecosystems in delicate balance with nature (Johannes, 1975; Endean, 1976; Loya, 1976; Loya and Rinkevich, 1980). Even Goreau (1969), who was the first to characterize modern reefs as youthful assemblages (mostly less than 5000 years in age) undergoing post-Pleistocene urban renewal (succession), referred to coral reefs as "delicately adjusted systems". Endean (1976) described the environment in which coral reefs thrive as "benign". Endean went on to claim that coral-reef communities are generally regarded as "very stable or predictable biotic associations because of the presence of a variety of buffering systems that protect the community against large scale destruction". Johannes (1975) argued that, since corals had evolved in stable tropical environments subject to narrow fluctuations in physical and chemical variables, they should be specialized and therefore highly sensitive to man-induced pollutants. Indeed, in a review of the subject (Johannes, 1975), the approach taken was to inventory numerous and various case histories documenting the effects of pollution on coral reefs, leaving the impression that coral ecosystems are highly vulnerable to pollution in general. Johannes went even so far as to suggest that "when a reef community is destroyed, the ecological conditions that follow cannot be expected to coincide with those preceding ... so it cannot be taken for granted that the reef community will *ever* replace itself". To various degrees, this view has been reiterated in the literature numerous times, for instance, "there are indications that when human activities are responsible for coral destruction, lack of recovery may prove to be common" (Endean, 1976); "man-made disturbances are more likely to result in permanent changes to the environment so that recruitment of coral communities may be prolonged, altered considerably or even prevented" (Pearson, 1981); "although some success stories and reversals have been reported, recovery of many ecosystems from previous impact will be incomplete or of long duration" (Maragos, 1986), and "human-perturbed coral reef environments will not return to former configurations while reconstruction of areas denuded by natural disturbance will" (Loya, 1976). Loya, of course, was referring to cases of chronic pollution in which the source or cause of environmental stress is persistent, an ecological circumstance that may be true for the duration of the stress-producing effect; but it is difficult to conceive such cases as being endless.

A somewhat contrasting theory of coral-reef ecosystem dynamics, first advanced by Grassle in 1973, is the view that reef communities form a "temporal mosaic" in space — that is, a patchwork of reef communities in different stages of recovery from various sources of disturbance; reef ecosystems are considered unstable, even unpredictable; change is considered more typical than constancy. In this view, the norm for reefs is suggested to be one of self-replacement and recovery from natural disturbance. In the 1970s, Grassle's temporal mosaic theory was to gather support from the work of Grigg and Maragos (1974) and Connell (1978), who both found that the successional processes on coral reefs were frequently disturbed by natural events. Connell's long-term studies of the Great Barrier Reef, in which he followed "permanent" quadrats, formed the basis of his now well-known "Intermediate Disturbance Hypothesis". According to this theory, the high diversity that characterizes some coral reefs is maintained by disturbance operating at intermediate levels. In 1982, Dollar described a major disturbance due to high waves in Hawaii causing massive mortality to all reef species, an event which returned the entire community to a low-diversity, early-successional stage. Many other earlier studies have documented the catastrophic effects of hurricanes and intense storm-generated waves (Stoddart, 1963, 1965, 1969a, 1974; Glynn et al., 1964; Cooper, 1966; Maragos et al., 1973; Hernandez-Avila et al., 1977) on coral reefs. Indeed, in Stoddart's review of coral-reef ecology, he stated that "the major cause of catastrophic coral mortality on reefs is mechanical destruction during tropical storms" (Stoddart, 1969b). These studies, in addition to more recent work on how changes in sea level have affected the growth, ecology and geomorphology of coral reefs during the Holocene transgression (Hopley, 1982; Grigg and Epp, 1989), leave little question today that coral reefs have evolved in a sometimes physically rigorous and unstable environment, and are well adapted to recovery from a variety of sources of natural stress [for a review see Pearson (1981); also Bak and Luckhurst (1980)].

The question regarding the degree to which coral reefs are susceptible to man-induced stress remains somewhat unsettled, and more work is needed before definitive conclusions can be drawn. In a comprehensive review of the subject, Brown and Howard (1985) concluded that "reef ecosystems may not be as fragile as previous generalizations would lead us to believe". Dollar and Grigg (1981) reached a similar conclusion after finding that the impact of a massive spill of kaolin clay at French Frigate Shoals, Hawaii, had only a trivial effect on the reef, and cautioned against generalizations about the vulnerability of coral reefs to man-induced pollution events. Nevertheless, there are many ecological questions associated with coral reefs that remain unsolved. Two examples are the recent mass mortality events of *Diadema* and widespread bleaching episodes of coral reefs in the Caribbean Sea (Ogden and Wicklund, 1988). Clearly, more fundamental long-term and large-scale ecological study is needed to develop a better understanding of coral-reef ecosystem dynamics.

In this chapter, the whole question of stress, both in terms of natural and man-induced effects, is re-examined in detail. The approach taken is to describe various case histories concerning both natural and anthropogenic stress to coral-reef ecosystems over various temporal and spatial scales, and by comparative analysis, attempt to develop a unifying theory.

Perhaps the most useful first step is a definition of terms. Brown and Howard (1985) discussed various interpretations of the term "stress" and settled on the definition of Rosen (1982) in which stress is viewed as a "gradient between ideal conditions and the ultimate limits of survival". In the discussion presented here, sublethal effects such as reduced growth or reproduction are recognized, but for defining stress it is felt that the use of a single parameter such as mortality (or survival) is a more useful, definitive and unequivocal measure. Stress is therefore defined as the degree of mortality (short- or long-term) to any species or species group comprising a coral-reef ecosystem caused by any process or event, either natural or anthropogenic.[1]

As suggested above, one possible index of stress (natural or anthropogenic) might be to measure net mortality of the system over time. Such a measure could be standardized and expressed in terms of survival by simply subtracting it from 1.0 (for instance, $1.0-X$) where X (mortality) could range between 1.0 (total destruction) and 0.0 (zero mortality). The expression (X) for mortality could then be partitioned into natural (N) and man-induced (I) effects, distinguishing relative differences and allowing the latter to be placed into perspective with the former. In virtually all studies of the effects of pollution on coral reefs, this has *not* been done, which possibly explains why reefs have been viewed as more "fragile" than they may

[1]The definition of "pollution" developed by the United Nations Educational, Scientific and Cultural Organiztion (UNESCO), Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), is as follows: "the introduction by man, directly or indirectly, of substances or energy into the marine environment resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of sea water and reduction of amenities". It is important to note that man-induced changes in parameters of water quality *per se* do not necessarily constitute pollution. In terms of our definition, pollution might be considered any factor that causes man-induced mortality to be greater than zero.

be (Brown and Howard, 1985). The index suggested above also has the advantage of being directly comparable to fisheries models in which total mortality (M) is partitioned into natural (N) and fisheries (F) mortality. It may be more than parenthetic to note that invariably, when F exceeds N to any significant degree, fisheries populations generally collapse (Gulland, 1970). Thus, it would seem that proper assessment of stress should entail a comparison of man-induced mortality (I) with natural mortality (N) over various spatial and temporal scales. Since the return period for many natural events causing significant stress is often on the order of decades, it would seem that proper assessment should take into account the temporal nature of the successional process (Grigg, 1983). It is also important to document relative spatial impacts — that is, the area disturbed as a proportion of the total area of a given habitat present.

NATURAL STRESS ON CORAL REEFS

Clearly natural stresses on coral reefs can range from trivial events causing insignificant mortality to intense storms (Stoddart, 1963; Maragos et al., 1973), volcanic eruptions (Umbgrove, 1930), major El Niño events (Glynn, 1985), massive sedimentation episodes (Hopley, 1982), population explosions of crown-of-thorns starfish *Acanthaster planci*[1] (Chesher, 1969; Dana et al., 1972; Endean, 1976; Pearson, 1981), and so on, all of which may cause massive, catastrophic and complete mortality to coral-reef ecosystems over large spatial scales. Two excellent reviews by Brown and Howard (1985) and Pearson (1981) provide detailed descriptions of the effect of such disturbances on coral reefs, which as mentioned vary from "no marked change" (Connell, 1978) to "total destruction" (Maragos et al., 1973). As might be expected, often effects are intermediate to varying degrees. Many such examples include mortality caused by disease (Antonius, 1985) predation (Robertson, 1970), low tides (Loya, 1976), low temperature (Shinn, 1972), volcanic activity (Grigg and Maragos, 1974; Pearson, 1981), red tides, earthquakes (Stoddart, 1969b), and other agents of natural destruction.

The question of assessing the impact of such stress events would seem to depend on their magnitude and return period (Dollar, 1982), and whether the latter is greater than the time necessary for recovery of the system. This problem has been addressed in particular with regard to analyzing differences in species composition and community structure of the coral reefs present off all the major islands, shoals, and atolls of the Hawaiian archipelago (Grigg, 1983). In this study, Grigg developed a theoretical model of succession, and suggested that differences between reef communities in comparable habitats off different islands are due largely to differences in successional age. For example, coral reefs off the Kona coast of the big island of Hawaii are frequently characterized by high cover, monopolization by one species (*Porites lobata* or *P. compressa* depending on depth) and, in general, low diversity. These reef systems are considered climax communities, space having been dominated by one species as a result of its competitive superiority in the absence of frequent disturbance. The return period of events sufficiently intense to set the successional process back to zero (total destruction of living corals) for the Kona coast has been estimated to be about 40 years (Dollar, 1982). Recovery of reefs on the Kona coast of Hawaii is estimated to require between 20 and 50 years (Grigg and Maragos, 1974), hence recovery time would appear most often to be less than the return period of severe disturbance events, probably accounting for the predominance of climax communities.

Gardner Pinnacles is an example of a reef ecosystem in the Hawaiian archipelago at the opposite end of the spectrum in terms of recovery time; it is a reef subject to intense and frequent wave disturbance, virtually awash on all sides during high surf and storms to which the island is subject at least 10 times annually. The reef ecosystem surrounding Gardner Pinnacles is characterized by low cover, high diversity and high equitability, all characteristics of a system frequently disturbed (Connell, 1978), in this case by harsh physical events.

Thus, in order to properly assess stress within any given ecosystem, it is important to contrast the magnitude and frequency of events causing stress

[1]Some authors consider *Acanthaster* population outbreaks to be primarily man-induced.

with natural recovery rates. While wave-sheltered dimensionally complex "old" reefs may take on the order of 20 to 50 years to recover fully (Grigg and Maragos, 1974; Pearson, 1981), systems which are "held" at an early stage (subclimax) of succession by frequent disturbance can be expected to recover to these early stages relatively quickly. It should also be noted that some assemblages such as shallow-water thickets of *Acropora cervicornis* may recover very quickly (*c.* 5 years: Shinn, 1972) due to rapid growth and structural simplicity. The net effect of stress in either case will depend on the frequency of the causative mortality event(s) in relation to the recovery time of the system(s). This argument should also apply over the long term. Thus, on a geological time scale, while the most significant change to occur over the last several million years may have been rises and falls in sea level, reef assemblages appear to have survived successfully by recovery at new depths faster than die-off rates caused by exposure or drowning, although changes in habitat area and isolation effects may have altered rates of speciation (Potts, 1985).

Having discussed problems dealing with measurement and assessment and the range of natural stress on coral reefs, both in space and time, we can now consider in a larger perspective the whole question of pollution and man-induced stress to coral reefs.

ANTHROPOGENIC STRESS ON CORAL REEFS

A comprehensive review of both effects and lack of effects of pollution on coral reefs was compiled by Brown and Howard (1985). A lengthy discussion of sublethal effects on growth, metabolism, loss of zooxanthellae, behavioral responses, mucus production, and reproduction is also given. A much earlier inventory of pollution events on coral reefs was published by Johannes in 1975. These reviews, in addition to other specific case-history studies, provide the basis of the analysis presented here. Rather than providing an all-inclusive review, only major sources of pollution and their effects to coral reef ecosystems are again reviewed in detail, although an attempt is also made to include mention of extremely serious impacts on more local scales.

Perhaps the most significant sources or potential sources of anthropogenic stress to coral reefs on a global scale are: (a) sedimentation (from dredging, erosional run-off, drill muds, sugar-cane wastes, etc.); (2) sewage effluents or other pollutants which cause eutrophication; (3) oil spills or detergents used in clean-up; and (4) heated effluents from power plants. Other sources of stress may cause more serious impact than the above problems, but damage is generally much more localized. Some examples include dynamite fishing (Philippines: Endean, 1976; Gomez et al., 1981), anchor damage (Florida: Dustan, 1977), nuclear tests (Eniwetok: Knutson and Buddemeier, 1973), coral mining (India and Sri Lanka: Venkataramanujam et al., 1981), shell-collecting (Great Barrier Reef: Endean, 1976), heavy rain coinciding with low tide (Hawaii: Banner, 1974), lava flows or volcanic eruptions (Hawaii: Grigg and Maragos, 1974; and Krakatoa: Umbgrove, 1930), and chilling (Persian Gulf: Shinn, 1972; Pearson, 1981). In exceptional cases, the magnitude of reef destruction due to a few of these activities or events can be substantial. In one region off southeastern India approximately 80 000 m^3 of *Acropora formosa* fragments, known as "challi" are collected for lime preparation each year, while massive corals are quarried at a rate of about 30 000 m^3 per year. And, in the Florida Keys, anchor damage (Dustan, 1977) has become a major destructive factor on some unprotected reefs; in marine sanctuaries mooring buoys have been placed to help lessen the impact (Halas, 1985).

In the sections which follow below, known physiological and ecological impacts caused by what are considered here the major sources of stress are carefully detailed. Emphasis is given to case-history studies which cover long-term and/or large-scale effects.

Sedimentation

The impact of increased sedimentation is probably the most common and serious anthropogenic influence on coral reefs. Sediment stress can be caused by activities that take place directly on the reef, primarily dredging and blasting for harbor construction (Dodge and Vaisnys, 1977; Sheppard, 1980), or by secondary effects resulting from physical alteration of the reefs. A classic case of such secondary effects was reported by Stoddart (1969b), who found that corals were completely eliminated from the lagoon at Palymra atoll, in the central Pacific, after a causeway was built across the atoll which restricted flushing and probably resulted in increased sedimentation and temperature, and a reduction in the plankton.

Sediment loading can also result from terrestrial activities that increase erosional runoff. Such "indirect" impacts on reefs appear to be especially important in developing countries such as the Philippines (Hodgson, 1988), Malaysia (Wood, 1979), Indonesia (Wijsman-Best et al., 1981) and Kenya (Brakel, 1984), where logging, agriculture and urbanization are presently causing substantial sedimentation in reef areas. In Hawaii, 29% of the coral reefs in Kaneohe Bay, Hawaii, were removed by dredging in 1939. Urbanization of the bay watershed also has caused large increases in runoff and sedimentation in the bay in the last 40 years (Banner, 1974). Impacts to Caribbean reefs from sediment influx have also been widely reported (Dodge et al., 1974; Rogers, 1985; Acevedo and Morelock, 1988).

The effects of sediment stress on corals have been reviewed by Levin (1970), Johannes (1975), Dodge and Vaisnys (1977), Bak (1978) and Brown and Howard (1985). While it is clear that increased sedimentation can have a deleterious effect on corals (especially when corals are completely buried), quantitative spatial or temporal data are not generally or readily available (Dodge and Vaisnys, 1977). Because sediments are suspended by natural processes in many reef environments, most corals can withstand a low sediment supply to the living surface. Many species have the ability to remove sediment from their tissues by distension of the coenosarc with water, or by ciliary action which can nullify lethal effects of sedimentation (Yonge, 1931). Hubbard and Pocock (1972) ranked species according to their sediment-rejection capacity, and the efficiency of removing different size classes of particles. Branching species had a distinct advantage over flat plating growth forms in remaining viable in situations of prolonged sediment deposition. Brown and Howard (1985) suggest that, where branching corals are observed to have suffered, it may be the result of light limitation, while, in instances where plating varieties are preferentially affected, it is likely that lack of sediment-rejection capabilities are the cause of mortality.

Dodge and Vaisnys (1977) suggested that sediment-rejection behavior is more efficient in terms of energy expenditure in smaller than in larger colonies. As a consequence, a major sedimentation event, such as dredging, might cause mortality of corals dependent partially on colony size.

In case studies dealing with effects of sedimentation, the range of environmental effects varies through the entire spectrum of stress. Dodge and Vaisnys (1977) found evidence that dredging activities in Castle Harbor, Bermuda, approximately 30 years ago caused a catastrophic mortality to corals in areas of confined circulation.

Marsalak (1981a) monitored a large-scale dredging project to replenish Miami Beach. Sand was taken from elongate trough-like depressions between parallel linear reefs. Scleractinian corals were tolerant to short-term (few days) sediment loading; but prolonged exposure to siltation and high turbidity resulted in loss of zooxanthellae, polyp swelling, and abnormal mucus secretion.

In field experiments designed to duplicate the effects of dredging, Rogers (1983) dumped sand on Caribbean reef corals in doses 1 to 3 orders of magnitude higher than natural rates of sedimentation. Cylindrical branching species were not affected, while flat branching species exhibited some tissue death, followed by recolonization of denuded areas by algae.

Finally, there have been instances of increased sedimentation reported that do not appear to cause any substantial effects on reefs. Sheppard (1980) reported that, following dredging and blasting for a military harbor in Diego Garcia lagoon, coral cover on several knolls appeared to show no long-lasting effects of siltation. The U.S. Army Corps of Engineers (1983) conducted an 11-year monitoring program to assess impacts from construction and operation of a public small-boat harbour that was built by blasting and quarrying a basin behind the natural shoreline. Results of surveys indicated no negative impacts to coral reef outside the entrance channel, rapid recolonization of the dredged area, and overall net increase in coral cover owing to colonization of new substrata inside the harbour basins.

A Greek freighter that ran aground on a reef at French Frigate Shoals in the northwestern Hawaiian Islands was refloated after 2200 tons of powdered kaolin clay were thrown overboard. Huge plumes of suspended clay raised major concern over the possibility of widespread ecological damage. Field investigations conducted 14 days after the kaolin dump revealed that environmental impact was very minor and highly localized. Coral damage was restricted to a small area where the ship's hull carved a channel through the reef, and a zone less than 50 m wide from the impact channel where thick clay deposits completely buried coral colonies. Beyond 50 m no corals appeared to be affected by the turbidity plumes, apparently because of rapid dispersal, and the benign chemical nature of the clay (Dollar and Grigg, 1981).

One specialized type of sedimentation is the dispersal of drilling muds used to lubricate and flush out rock cuttings excavated by drill bits during oil exploration. Hudson et al. (1982) examined coral reefs that were the site of offshore drilling off the Palawan Islands, Philippines. While coral cover was reduced in an iron-stained area centered around the wellheads, X-radiographs of colonies of *Porites lutea* indicated little suppression of growth attributable to the effects of drill muds. Hudson et al. (1982) concluded that drill muds, when compared to other aspects of drilling, constitute a minor threat to coral growth.

Using drill mud from a land-based drilling operation, Szmant-Froelich et al. (1981) performed physiological studies of *Montastrea annularis* in the laboratory over a period of 6 weeks, using concentrations of 1 to 100 p.p.m. At a concentration of 100 p.p.m. the drill mud had a pronounced deleterious effect on respiration, photosynthesis, calcification, and nutrient uptake. However, extrapolation of these laboratory results to the field must be done carefully, because concentrations of 100 p.p.m. would rarely be found in the field. Concentrations of 1 and 10 p.p.m. had little effect when compared with controls.

Sewage and eutrophication

The most important parameters of sewage stress in marine environments appear to be the degree of oxygen depletion, amount of toxic contaminants and level of sewage treatment. Effects of sewage pollution on coral-reef communities have been reviewed by Pastorek and Bilyard (1985). Sewage may contain significant amounts of toxic materials or toxic byproducts from pesticides, herbicides, chlorine, or heavy metals. High biochemical oxygen demand (B.O.D.) from the sewage, possibly coupled with hydrogen sulfide generation, might also impose toxic effects. Alternatively, materials in sewage effluent might represent a nutritional subsidy, causing increased biomass and productivity and leading to altered community structure.

To date, most of the reported sewage-related effects on coral reefs have been the result of the stimulatory (nutrient subsidy), rather than the inhibitory (toxic), nature of sewage effluent. In general, detrimental effects of nutrient subsidy appear to be caused by shifts in competitive advantage toward species that outcompete corals. In microcosm experiments using a variety of treated effluents, Marsalak (1981b) found that the most pronounced effects on coral morbidity and mortality were not directly related to effluent toxicity, but were the result of competition with algae for space and light. Walker and Ormond (1982) also found localized mortality of corals resulting from sewage discharge and spillage of phosphate dust during loading of ships in the Red Sea. They observed decreased diversity and an abundance of damaged colonies as well as colonies overgrown by filamentous algae near the outfall. While the mechanisms for the changes to corals were not readily apparent, it appeared that the increased nutrient load caused algae to gain a competitive edge. Sediment trapped by the algal mat may have also spread to the coral tissue, placing it under further stress and hastening its death.

Without question, the most thorough analyses of the effects of domestic sewage on coral reefs have taken place on the island of Oahu, Hawaii. These studies are especially significant because they include documentation of environmental effects resulting from sewage discharge, as well as responses of the reef community following elimination of the sewage stress.

Perhaps the best-known example of sewage stress on a reef community is Kaneohe Bay, a semi-enclosed embayment on the northeast coast of Oahu. From 1963 to 1977, point-source discharge of secondary sewage entered the bay from three outfalls, with a total peak flow rate of 1.9×10^4 m^3

day^{-1}. In 1978, the sewage was diverted to a new deep-ocean outfall offshore, eliminating all but a small volume of discharge in the northwest lagoon. During peak sewage discharge essentially no live corals were observed in the south bay, possibly as a result of anaerobic conditions in the sediments leading to a release of hydrogen sulfide. In the central and northern sectors of the bay, sewage nutrients supported extremely dense growths of the "green bubble algae", *Dictyosphaeria cavernosa*, which smothered much of the reef corals and associated fauna (Maragos, 1972).

In 1983, five years after diversion of the sewage, total live coral coverage as a whole had increased dramatically, almost doubling in abundance. In the south bay many small coral colonies were present, although abundance was still only a fraction of that in other regions. Notable coral recovery on old dredged surfaces was observed in the south lagoon, but deteriorated reef surfaces covered with sediment were still devoid of colonization. By 1983 *Dictyosphaeria* had decreased by 75% overall, with the greatest reduction in the areas where the alga had previously exhibited peak abundance. Maragos et al. (1985) reported that the alga increased in abundance in 1983 relative to 1971 in the north bay station nearest the small sewage outfall that was still discharging sewage at the time of the 1983 survey. These authors pointed out that it was difficult to distinguish the negative effects of sedimentation from those of sewage discharge in Kaneohe Bay, since both were concentrated in the south bay during the same time. In like manner, coral recovery has occurred during a period when both of these stresses have been substantially reduced. While the negative effect of these two factors in Kaneohe Bay undoubtedly involved a degree of synergism, removal of both sources of stress appears to have resulted in rapid recovery.

Another case of severe sewage impact to reef communities in Hawaii occurred at the Sand Island sewage outfall, Oahu. From 1955 to 1977, up to 2.5×10^5 m^3 day^{-1} of raw domestic sewage was discharged 1000 m from shore into a coral-reef environment at a water depth of 10 m. In the immediate vicinity of the outfall, turbidity was high and the water column was heavily laden with particulate organic matter of sewage origin. The major effect on community structure was the total destruction of corals within 400 m of the outfall terminus. In their place, an arenaceous polychaete *Chaetopterus* dominated bottom cover near the outfall. Stations at intermediate distances from the diffuser had species associated with both normal and sewage-dominated environments, producing an assemblage with relatively high diversity (halo effect: Grigg, 1978). In this zone, large numbers of the dominant coral species, *Porites compressa*, were dead but intact. The area of sewage influence was asymmetrical to the west, due to the prevailing current flow which carried the sewage-laden plume to the southwest (Grigg, 1975).

One year after diversion of the Sand Island discharge to a deep ocean outfall the process of recovery was under way (Dollar, 1979). Around the outfall the substratum was marked by two distinct zones of impact distinguished by the degree of physical degradation of the reef platform. A high-impact zone previously occupied by *Chaetopterus* worms was characterized by a complete biochemical reduction of the reef structure to a pitted, limestone pavement covered with a sediment-bound algal turf. In the zone of previous intermediate impact, most of the reef coral assemblages that developed during the "pre-outfall" period were dead and encrusted with a veneer of coralline algae. Small corals were observed to be recolonizing both zones of severe and intermediate impact.

While the Kaneohe Bay and Sand Island case histories describe serious man-induced damage to coral communities, recovery appears to have begun soon after termination of the sewage stress. Parenthetically, in both cases diversion of sewage to deep open-ocean outfalls has totally eliminated impacts to the entire marine ecosystem (Russo et al., 1981; Laws and Terry, 1983; Dollar, 1986). Outfall design utilizing multiport diffusers, and sewage treatment that removes large particulate material, appear to have been effective in reducing the concentration of effluent that reaches the benthos. Probably the most important aspects of the new outfall is that it is located in water depths deeper than optimal for reef growth and it is exposed to strong currents and unrestricted water circulation. Because of multiport diffusers, dilution and dispersion appear to be sufficient to negate the potentially detrimental effects of ocean sewage discharge.

Oil

Because of catastrophic damage to marine environments from major oil spills such as those from the *Amoco Cadiz* and the *Torrey Canyon*, there is a great deal of concern regarding the potential effects of oil pollution on coral reefs. Yet, data on the fate and effects of petroleum hydrocarbons on coral systems are relatively limited, and in some cases contradictory [see reviews by Johannes (1975), Loya and Rinkevich (1980), Knap et al. (1983), and the National Research Council (1985)].

Most studies of the effects of oil on corals have been conducted in the laboratory. Field studies depend on spills of opportunity which are infrequent and highly unpredictable. The rationale behind most of the laboratory studies is that potentially unseen physiological damage to coral-reef communities must be addressed prior to concluding that there are no harmful effects if organisms appear to be in good health following an oil spill (Birkeland et al., 1976; Loya and Rinkevich, 1980). A wide range of physiological response to oil has been observed in laboratory studies of corals, including decreases in growth (Birkeland et al., 1976), reproduction and colonizing capacity (Loya and Rinkevich, 1979; Peters et al., 1981), negative effects on feeding and behavior (Reimer, 1975), and alteration of the secretory activity of mucus cells (Peters et al., 1981).

Laboratory studies have also revealed that negative impacts are sometimes lacking. Bak and Elgershuizen (1976) found that patterns of oil-sediment rejection by hermatypic corals were identical to patterns of rejection of clean sediments. They also found no evidence of oil adsorption on living coral tissue, and no active ingestion of oil drops by corals. Reimer (1975) found that four species of corals from Panama survived short (0.5–30 min) immersions in crude oil. Survival with "no apparent effect" varied with the type of oil, length of exposure and the coral species.

Obviously, the results of laboratory studies must be critically evaluated before they can be equated with field conditions. Experimental concentrations of oil or hydrocarbons, and modes of exposure used in laboratory experiments, frequently do not appear to accurately mimic conditions encountered in actual spills.

It appears that the most important factor distinguishing instances of negative impact from those of no apparent impact on coral reefs is chronic stress versus "one-time exposure". Loya and Rinkevich (1980) emphasized that chronic events are apt to be more detrimental than isolated episodes, even though the latter are more visible at the time they occur. The site where the effects of chronic oil pollution have been most studied is the reef flats in the northern Gulf of Eilat, Red Sea (Loya, 1975, 1976; Rinkevich and Loya, 1977, 1979; Loya and Rinkevich, 1979; summarized by Loya, 1980). Chronically oil-polluted areas of the reef showed higher mortality rates of colonies, smaller number of breeding colonies, a decrease in the average number of ovaria per polyp, smaller number of planulae produced per coral head, and lower settlement rates of planulae on artificial objects.

Loya (1976) used observations of community and physiological response as a basis for analyzing the effects of anthropogenic influence on coral community recolonization. The recovery patterns of the oil-stressed reef were compared to a control reef following an unpredicted catastrophic low tide. Ten years after the event, the control reef was flourishing with a recolonized community structure similar to the original community, while on the chronically oil-polluted reef practically no recolonization was evident. Although no direct evidence was apparent that oil damaged hermatypic corals, the data suggested that chronic oil spills prevented normal settlement and/or development of coral larvae.

Single-event episodes of oil exposure have rarely been shown to have detrimental effects on reef communities. In a summary of effects of 16 oil spills near coral reefs, there are no specific reports of damage to corals (National Research Council, 1985). Even in some areas subjected to chronic oil exposure such as Tarut Bay, Saudi Arabia (Spooner, 1970), the Persian Gulf, and near the entrance to the Suez Canal (Shinn, 1972), no damage to reef communities has been observed.

One reason why the effects on corals from actual spills have been minimal may be that the reef surfaces are rarely exposed to oil at the air–sea interface. Johannes (1975) stated that there is no evidence that oil floating above reef corals causes noticeable damage. Rutzler and Sterrer (1970) reported that reef corals escaped noticeable damage from a spill of diesel oil off Galeta Island, in the Panama Canal Zone, because they were continually submerged. Intertidal organisms appear to be affected to a greater extent than corals, because the former are more likely to be actually coated by oil. Reefs that are exposed to air coincident with oil on the sea surface may well suffer lethal effects (Johannes et al., 1972).

Finally, the detergents used to disperse spills may be a more serious potential pollutant than the oil itself. Lewis (1971) found that Caribbean corals were sensitive to exposure to crude oil to a lesser degree than to the oil dispersant "Corexit". Elgershuizen and De Kruijf (1976) also found that a mixture of oil and dispersant was more toxic to the stony coral *Madracis mirabilis* than the two constituents separately. They concluded that, in the case of a major oil spill, reefs are more endangered by clean-up with chemical detergents than by the oil itself.

Thermal stress

The potential threat to marine organisms of elevated temperatures has been reviewed by Johannes (1975). Sublethal temperature effects on corals include depressed feeding responses, reduced reproductive rates, increased zooxanthellae and mucus extrusion, and a decrease in the photosynthesis/respiration ratio. Because the biota of tropical regions characteristically live at temperatures only a few degrees below their upper lethal limit, they may be more susceptible to elevated temperature than temperate or polar communities.

Studies of thermal tolerance in hermatypic corals have primarily been limited to laboratory investigations involving short-term exposure to lethal temperatures (Mayor, 1917, 1918; Mayor, 1924; Edmondson, 1928; Yonge and Nicholls, 1931). Johannes (1975) pointed out however, that because organisms may not be able to tolerate temperatures as high in nature as they do under controlled conditions in the laboratory, caution must be used when extrapolating the results of short-term incubations to effects in nature.

Field studies of anthropogenic thermal enrichment are limited to the effects of heated effluent used to cool generators in power plants. Heated water pumped into Biscayne Bay, Florida from a power plant on Turkey Point reduced the diversity and abundance of algae and animals in a small area adjacent to the mouth of effluent canals (Roessler and Zieman, 1969). Corals (*Siderastrea* sp.) were killed as far as 725 m from the canals. Temperatures of 4°C above ambient killed nearly all fauna normally present in an area of about 50 ha. The area contained within the +4° and +3°C isotherms was characterized by an increase in detritus feeders due to large amounts of dead and decaying organic material.

On Guam, heated effluent from a power plant led to the destruction of reef margin corals in a zone of 4320 m^2 and damage to a peripheral area including a total of 10 000 m^2 (Jones and Randall, 1973). Determining the specific response of corals to thermal conditions, however, was complicated by the fact that the cooling water contained significant levels of chlorine and copper, which served as de-sliming and anti-fouling agents.

Jokiel and Coles (1974) evaluated the effects of an increase in coolant discharge that accompanied expansion of the Kahe Power Plant on Oahu, Hawaii, and the effects of heated discharges before and after. Effluent was discharged from an outfall on the shoreline and was dispersed across a shallow reef flat. Abundances of dead and damaged corals correlated strongly with proximity to plant discharge and levels of thermal enrichment. Nearly all corals in water 4 to 5°C above ambient were killed. In areas characterized by temperatures 2 to 4° above ambient, corals lost zooxanthellar pigment and suffered high mortality rates. Damage to the corals was most severe in the late summer, and coincided with ambient temperature maxima. During the winter months the surviving corals slowly gained zooxanthellar pigment, but there was high mortality of corals during the recovery period. When the generating capacity of the plant was increased from 270 to 360 megawatts, the area of dead and damaged corals increased from 0.38 ha to 0.71 ha.

In 1976, an offshore outfall was constructed at the Kahe power plant which diverted the effluent from the beach outfall to a depth of about 4.0 m. Coles (1984) monitored the response of the coral communities to the discharge of heated effluent for seven years, and found that the deleterious effects had been eliminated by relocating the discharge to deeper waters. In fact, on the deep outfall, Coles found that the number of colonies and area coverage of corals increased exponentially with proximity to the discharge. Coles speculated that entrainment of coral planulae in the warm discharge water caused a physiological response that resulted in immediate settling behavior. However, the transects nearest the outfall were placed on the diffuser structure. Therefore, it is possible that the high rates of coral recruitment may have been the result of settlement of planulae to available space situated in an optimal environmental setting. Regardless of the mechanism responsible for increased colonization at Kahe Point, Oahu, the significant result of Cole's study is that reorientation of the thermal plume to avoid direct contact with corals completely eliminated all detrimental environmental influence.

CONCLUSIONS

One of the most important limitations in assessing the effects of stress on coral reefs is the general lack of quantitative data (spatial and temporal) covering both natural and man-induced impacts. In the literature, stress is commonly described as any measureable change in physiology or state (percent living cover, alive to dead ratio, diversity, community structure, number of species, etc.) and rarely has there been any attempt to distinguish natural from man-induced causal factors. In the section of the proceedings of the Fifth International Coral Reef Congress held in Tahiti in 1985 devoted to protection and conservation of reef environments, in a summary paper subtitled, "A gamble on the future", Arthur Dahl created the impression that man-induced stress is global in scope and catastrophic in nature. The reefs of Okinawa and Tonga were described, respectively, as 80% and 65% damaged, and yet no attempt was made to distinguish what fraction of either was due to natural mortality. Such generalizations are surprising in view of the many examples in the literature where literally tens of kilometers of reef have been totally destroyed by a single hurricane or typhoon (see earlier references).

The general lack of quantitative rigour in the literature as applied to the assessment of stress is also evident in the present review. For example, the effects of sedimentation are shown to range across the board from total destruction to being unmeasurable. On what scale? Over what time frame? Relative to what area unaffected? In order to rectify this situation, we suggest the following approach to the problem:

(1) that a quantitative definition of stress be adopted; we suggest the measure $1.0-(I+N)$ where I=annual mortality due to anthropogenic effects and N=annual natural mortality;

(2) that man-induced mortality always be compared to natural mortality, perhaps I/N;

(3) that the frequency of the disturbance causing mortality be compared with the recovery time of the system;

(4) that the area disturbed or destroyed be compared to the total habitat area present, perhaps A_I/A; and

(5) that sublethal effects be documented, particularly as they may lead to long-term increases in mortality or reduction in recruitment and growth.

While it may be impractical or even impossible to document stress to this degree, the adoption of a more quantitative approach to the study of the problem should create a more objective understanding of coral-reef dynamics than currently exists. A directory of all major coral reefs in the world was recently compiled by the International Union for the Conservation of Nature (Wells, 1988). In this document, an attempt is made to distinguish between man-induced and natural stress, and this should greatly aid in obtaining a new perspective.

Turning to more theoretical aspects of the problem of ecosystem dynamics, two rather contrasting schools of thought now seem to prevail. One is that coral reefs are in "delicate balance" with nature and are relatively sensitive to man-induced stress (Johannes, 1975; Endean, 1976). The other position is that coral reefs form a "temporal mosaic" in dynamic flux, in which disturbance and self-recovery are the norm (Grassle, 1973; Grigg and Maragos, 1974; Connell, 1978). In practice, there may not be as much difference between these theories as it seems. Certainly, workers in the first school acknowledge the devastating effects of hurricanes, as well as biotic factors such as *Acanthaster* predation which have been described as "massive" (Endean, 1973, 1976), and yet the notion that reefs are in fragile balance with nature and highly susceptible to pollution still seems entrenched in this body of literature. Such a view may have evolved in part as a reaction in the late 1960s and early 1970s to other extremely serious global environmental concerns dealing with radionuclides, DDT (dichlorodiphenyltrichlorethane) and other persistent polychlorinated hydrocarbons (Chesher, 1969; Halstead, 1970). A cautious view would also seem justified by the fact that man-induced impacts on coral reefs could be expected to be cumulative with natural disturbance. Conservatism is also appropriate given the long recovery times of coral ecosystems (Pearson, 1981) and because many economies which are dependent on coral-reef resources are at the subsistence level. Further, chronic effects would be expected to retard regrowth even beyond natural recovery times (Loya, 1975, 1976). All of these apprehensions are valid concerns, and in practice are equally recognized by the "temporal mosaic" school. While under the latter theory reefs are viewed as constantly undergoing change and resilient in nature, it would be no less necessary to exercise caution in the application of management and conservation measures.

One rather positive conclusion that seems evident from this review is that the technology to mitigate impacts of many sources of anthropogenic stress are presently available. It is now well known that placement of sewer outfalls at depths below reef growth is highly beneficial (Dollar, 1979, 1986), and the engineering know-how to do this is readily available. The case history of sewage abatement in Hawaii shows this. Deep-water disposal also is extremely effective in mitigating the effects of thermal enrichment on coral reefs (Coles, 1984). For oil clean-up, containment booms and adsorbants have proved to be reasonably successful. Sediment plumes can also be confined or diverted as in the case of Kaneohe Bay, Oahu, where recovery of reef ecosystems has been immediate and reasonably rapid (Maragos et al., 1985).

Another positive result brought out in this review is that recovery from man-induced stress would not appear to be qualitatively different from recovery from natural stresses. This clearly contradicts the suggestions of Johannes (1975) and Loya (1976) that recovery from anthropogenic stress may be "qualitatively different" and that polluted reefs may "never" regain their configuration before the stress. Case histories of sewage outfalls and power plants in Hawaii exhibit patterns of rapid recovery, once stress has been terminated. Only when reefs are subjected to chronic stress is recovery retarded (Loya, 1976).

Finally, when comparing anthropogenic stress with natural stress it is perhaps premature to conclude which of the two is more pervasive. However, we have shown that nature certainly can be as perverse as man, and often is so on a very large scale [50–65 km of reef devastated in British Honduras (Belize) due to a hurricane (Stoddart, 1963)]. Also, if one takes a longer view, the perversity of nature is again borne out by the fact that Holocene reefs are in general less than 7000 years old, having been formed during the process of post-Pleistocene recovery from local extirpation caused by a sea-level drop of about 130 m 18 000 years ago (Goreau, 1969; Hopley, 1982; Grigg and Epp, 1989).

Nevertheless, while coral reefs may not be more susceptible than numerous other ecosystems to pollution, it is extremely important to conserve their resources for numerous and various benefits to mankind. It is also becoming clearer that, while coral reefs are highly productive ecosystems (Odum and Odum, 1955), the ratio of productivity to respiration is frequently close to 1.0 (Kinsey, 1979), rendering them extremely vulnerable to overfishing (Grigg et al., 1984). Indeed, overfishing, although not normally considered a pollutant, is certainly a man-induced stress, and may be the single most serious form of anthropogenic destruction of coral reefs in the world (Dahl, 1985; Wells, 1988). It seems safe to say that overfishing has produced an extremely serious need for better management of coral-reef resources on a global scale.

In conclusion, we would reiterate that caution be exercised in evaluating man-induced impacts. An example from Puerto Rico is one case in point. For years the reefs of Vieques Island, Puerto Rico, have been used as a bombing range. Litigation against the United States Navy claimed that bombing was promoting excessive sedimentation and turbidity on nearby offshore reefs. Studies by the Florida Reef Foundation, however, concluded that military impact was negligible when compared to natural damage caused by storm-generated wave action. Reefs of the bombing range seemed slightly healthier in terms of diseased and/or dead corals than control reefs in the Virgin Islands (Dodge, 1981; Antonius and Wiener, 1982). The lack of impact of a massive spill of kaolin clay at French Frigate Shoals, Hawaii, is another reminder of an event with serious expected impacts that produced virtually none (Dollar and Grigg, 1981). But the building of a causeway across Palmyra atoll, which killed an entire lagoon of coral, proves the reverse is also true.

Thus, in attempting to develop a unified theory it would appear that there is little qualitative difference between anthropogenic and natural stress to coral reefs, and that both sources of disturbance are important in controlling reef community structure. Nature can be and often is more perverse than man. In terms of application, we would argue that the best approach is one of treating each instance of stress (natural or anthropogenic) on a case-by-case basis. Even though coral reefs may be well adapted over the long term to surviving stress, the need to develop sound management practices is becoming increasingly more urgent as population growth and man's uses of reef resources continue to escalate. We would also argue that the development of a quantitative index for measuring stress would greatly aid in the relative assessment of natural versus anthropogenic impact. Impacts should also be assessed in terms of frequency of disturbance in relation to recovery time, and the area disturbed in relation to the total area present. Reefs may be capable of natural recovery, but this does not lessen our need to develop a sound basis for management and a clearer understanding of their ecosystem dynamics.

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REPRINTED FROM:

ECOSYSTEMS OF THE WORLD 25

CORAL REEFS

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PROPOSAL TO DEVELOP STANDARDIZED PROTOCOLS TO MONITOR CORAL REEF ECOSYSTEMS

INSTITUTIONAL FRAMEWORK

The Environmental Protection Agency (EPA) would like to initiate an interagency program with the National Oceanographic and Atmospheric Administration (NOAA) to develop standardized monitoring methods to evaluate the ecological health of coral reef ecosystems. Coral reefs are recognized aquatic resources, and assessment tools for reefs would aid environmental management programs in the Pacific Basin, the Caribbean and throughout the world.

For EPA, reef monitoring metrics would be applied by U.S. flag states and territories to assess the impacts of pollution to the designated uses of near coastal waters, and the attainment of Clean Water Act goals in those regions.

For NOAA, standardized reef monitoring metrics will facilitate the management of marine resources and the development of multinational monitoring networks that could evaluate global climate change impacts.

For both agencies, the coordination of coral reef monitoring activities and adoption of similar monitoring activities would improve data comparability and allow the development of integrated strategies for the protection of coral reef resources.

It is proposed that the development of standardized reef monitoring methods begin by convening of a coral reef monitoring conference for scientists and agency representatives. This will be a facilitated conference, and scientists and agency representatives will present and discuss the strengths and weaknesses of various approaches to monitoring reef ecosystems, within the context of agency environmental management objectives. A conference proceedings will be published.

It is anticipated that this conference will lead to the formation of a working interagency committee to recommend and arrange for pilots of standardized monitoring protocols and metrics, and the publication of a joint EPA/NOAA guidance manual for coral reef monitoring. This proposal is only for the conference and publication of proceedings.

We would like to hold the conference in Hawaii, to take advantages of facilities at the University of Hawaii, to address the political urgency of addressing algal bloom impacts to reefs in West Maui, and to involve Pacific Basin countries. The conference could be coordinated to dovetail with proposed U.S. Senate hearings on coral reef ecosystem protection legislation.

BACKGROUND

The coral reef ecosystem is one of the most complex, rich and biologically productive environments. Not only do coral reefs provide habitat for a myriad of other organisms, but they also provide crucial nutrients retained from the waste products of symbiotic algae in their tissues. Many barrier reefs shelter the coastline from storm surge and waves, prevent coastal erosion & add to the formation of beaches & protected harbors. Coral reefs play an integral part in the human economy and welfare, particularly in the industries of fisheries, tourism and pharmaceuticals.

Presently, coral reefs cover approximately 2 million km^2 of the tropical oceans alone (Dubinsky, 1990). Reef-building corals, or hermatypic corals, abound in the Atlantic, Pacific, Indian Oceans and Red Sea, and are primarily restricted to the regions between the latitudes 30° N and 30° S (UNEP/IUCN, 1988). Since these corals are light-dependent, their distribution decreases with depth, which primarily confines them to near coastal zones. Consequently, human activities are increasing in this natural environment which is being stressed, impaired, or destroyed in many parts of the world.

The urbanization of coastal areas has led to sewage pollution in many coral reef communities. Inadequate or lack of sewage treatment facilities in less developed areas pose the greatest threat to coral reef communities along the coast. In fact, less than 10% of all domestic sewage is treated before it is discharged, and much reaches coastal waters (Brown and Howard, 1985). Domestic sewage may lead to eutrophication, an increase in organic and mineral nutrients. Eutrophication accelerates algal growth which smothers the coral and introduces undesirable species such as pathogens harmful to man and reef organisms (Marszalek, 1987). One such area with such historical sewage pollution effects is Kanehoe Bay, Hawaii. The community structure was altered by increases in phytoplankton, benthic algae, filter-feeders, and the fatality of corals (Marszalek, 1987). After diversion of the sewage effluent outfalls to a remote location in 1978, the reef community continues to recover and requires continued monitoring to determine the reversibility of the pollution effects. Other areas of Hawaii near sewage effluent discharges have been recently impacted by high nutrient levels and algae blooms, including Maui. Yet another area impacted by sewage pollution has been on the southeast coast of Florida, where over 2 million people contribute to waste dumping (UNEP/IUCN, 1988). Pathogenic viruses from these sewage effluents threaten humans using beaches and eating shellfish.

Long-term studies have shown that oil pollution may cause significant damage to reef corals. Tanker spills have severely damaged reefs in the Florida Keys and Puerto Rico (UNEP/CEPAL, 1982). Even more severe may be the damage from clean-up operations following spills due to the toxicity of chemical detergents (Loya and Rinkevich, 1987). In addition, oil drilling fluids from oil platforms in the Gulf of Mexico contain complex mixtures of biocides and lubricants (UNEP/IUCN, 1988). Heavy metals from these discharges have also contaminated fish populations in many Gulf of Mexico reefs (Taylor and Bright, 1973).

Thermal effluents from marine power plants can cause severe harm in areas with restricted circulation. For example, a discharge site for the Turkey Point Station at Biscayne Bay, Florida resulted in extensive thermal mortality of coral reefs due to poor lagoon circulation at the discharge point (Zieman and Ferguson, 1975).
In addition, the thermal effluent from the Tanguisson Power Plant in Guam destroyed a reef plane and margin area of 20,000 square miles due to increased water temperature and heavy metals (UNEP/IUCN, 1988). Thermal pollution can also cause higher incidence of disease and bleaching (the expulsion of symbiotic zooxanthellae) in corals (UNEP/IUCN, 1988)

Dredging in or near coral reefs can have devastating effects on corals due to heavy sedimentation. The fine particulates carried by currents to reef communities smother coral surfaces and increase turbidity which reduce light levels, eventually causing mortality (Salvat, 1987). In Kaneohe Bay, Hawaii, a combination of dredging, run-off, and sewage effluent resulted in no coral growth in one third of the bay (UNEP/IUCN, 1988). As coastal urban areas expand, dredging activities to create or deepen harbors are on the rise. In addition, stony corals have been used for building material in the production of lime and cement. The removal of coral through mining has resulted in severe beach erosion and movement of sand to adjacent reefs (Dubois and Towle, 1985).

Land run-off is probably the most significant contributor of sediment to coastal waters, and the impacts of sedimentation upon coral reefs can be the most devastating. With nearly 1.8 million hectares of forest disappearing each year in the Wider Caribbean region (UNEP/CEPAL, 1980), increased erosion and run-off have caused noticeable siltation on reefs off South America and in the Caribbean (UNEP/IUCN, 1988). Coastal sedimentation levels are also high in the Hawaiian islands due to urban development and agriculture (UNEP/IUCN, 1988). Other coastal inputs that can further increase coastal pollution in coral reefs include fertilizers, pesticides, and drainages from storm drain canals.

Sugar industries and distilleries can have an impact on reef coral community structure. Sugar mill waste discharges are characterized by high biological oxygen demand (BOD), high pH levels, and suspended solids (UNEP/IUCN, 1988). A recent study researching the marine environmental impacts of the Pepeekeo and Haina Mills, Hawaii sugar mills off the northeast coast of Hawaii, showed that corals were totally absent directly off two mill discharge sites (Tetra Tech, 1989). Within the mixing zone boundaries, coral cover was substantially lower than cover beyond the boundaries. In addition, many Caribbean countries (including Puerto Rico) support sugar industries that may be impacting coastal coral reef communities.

Some of the more difficult impacts of human activities to assess include coral/shell/ and fish collections for jewelry, decoration, and aquaria. Over-exploitation of reef species is on the rise in countries that rely on tourism. Destructive methods for collecting aquarium and food fishes include the use of fish poisons (sodium cyanide, insecticides, and ichthyocides) and even dynamite (Randall, 1987).

Protection of reef ecosystem resources begins with monitoring. Regulatory and resource agencies need to know if the changes that are reported in the biological structure of coral reefs are caused by pollution from human activities, by global scale climate changes, or by natural cycles of variation. They need to be able to predict whether the measures they institute will actually be protective. They need to adopt long range strategies among agencies that will protect reef ecosystems from further degradation. Moreover, they need monitoring information on spatial and temporal scales that match the scales of their environmental management decisions.

Scientists have studied coral reefs extensively, and understand their structure, dynamics, and sensitivity (UNEP/IUCN, 1988). The monitoring techniques developed by coral reef scientists will thus serve as a basis for developing agency protocols, and the elements for developing monitoring tools will be institutional as well as scientific. What is needed is a general consensus among scientists that the methods to be adopted are sensitive and can be applied over a large spatial scale, and then coordination among agencies to adopt similar methods. If uniform monitoring methods are adopted, then monitoring networks can be developed among agencies that will provide the kinds of information, in the right spatial and temporal scale, that will permit managers to make wise decisions for the protection of reef ecosystem resources.

REEF MONITORING CONFERENCE:
RAPID BIOASSESSMENT STRATEGIES FOR CORAL REEFS
TENTATIVE AGENDA

The conference will be a three day workshop focusing on the development and application of rapid bioassessment methods for assessing the biological condition of coral reefs. This conference will bring together leading experts in coral reef ecology and monitoring strategies. Rapid bioassessment of coral reefs is not a new concept and several candidatae procedures are currently in use around the world. The conference agenda will center on specific topic areas that are of importance to regulating agencies charged with the responsibility of protecting coral reefs. A proceedings, which includes manuscripts from the presenters as well as sommaries of work group sessions wiould be produced to serve as a guidance document.

SUGGESTED WORKSHOP TOPICS
(SUBJECT TO REVISION)

Introductory Materials
- -Purpose of conference
- -Regulatory framework
- -Concept of rapid bioassessment or cost-effective strategies
- -Implementation of biological criteria

Response Signatures of Coral Reefs
- -Coral reef bleaching
- -Bioerosion
- -Predator-prey imbalance
- -Species losses
- -Physiological manifestations
- -Other?

Cost-Effective Bioassessment Strategies
- -Remote Sensing
- -Diving reconnaissance
- -Color detection
- -*in situ* photography
- -Other?

Management Concern
- -Public awareness and concern
- -Coastal engineering practices
- -Enforcement and regulation
- -Attainment of biocriteria
- -Other?

Workshop Sessions
- -Appicability of biocriteria
- -Methods Selection
- -Role of marine reserves in coral reef conservation
- -Other?

PROPOSED TASK LIST AND COST ESTIMATES

Task 1. Conference Organization and Administration
- -Organize elements of workshop and finalize agenda
- -Provide logistical organization
- -Develop flyers and snnouncements for invitees
- -Arrange conference facilities and housing

Estimate: $20,000

Task 2. Technical Coordination
- -Assemble contributors and presenters
- -Prepare technical materials and format
- -Coordinate contents and specific agendas of sessions

Estimate: $15,000

Task 3. Conference Facilitation and Participation
- -Coordinate on-site logistics
- -Participate in presentation of selected topics.
- -Facilitate and monitor sessions
- -Compile workshop notes and identify key issues

Estimate: $15,000

Task 4. Conference Proceedings
- -Provide guidelines for proceedings
- -Coordinate manuscript submittal and review
- -Provide technical editing
- -Provide camera-ready copy for publication

Estimate: $25,000

Task 5. Travel Support
- -Provide travel support for selected State agency personnel and conference presenters

Estimate: $30,000

TOTAL: $105,000

PROPOSED BUDGET

EPA Region 9 -- $30,000 (Maui Algae Bloom Appropriation)
EPA Region 4 -- $15,000
EPA Office of Water -- $30,000
NOAA -- $30,000 (Maui Algae Bloom Appropriation)

JUSTIFICATION FOR USE OF MAUI ALGAE BLOOM APPROPRIATION

The coral reefs in West Maui are the primary ecosystems that are impacted by the algae blooms. There is a real concern that degradation of the West Maui reef system will have both an economic impact and an impact on a valuable natural resource. It is anticipated that the Maui Algae Strategy to be developed by EPA and the State of Hawaii will have a coral reef monitoring component to measure the effectiveness of the management measures imposed on the watershed. The Coral Reef Monitoring Conference will propose protocols for standardized reef monitoring that can be implemented on the West Maui reefs. Hopefully, a volunteer monitoring program using local divers can be organized using protocols developed by the conference.

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